Implications of Information Technology for Employment, Skills, and Wages: A Review of Recent Research

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Executive Summary

The extraordinary diffusion of computers and information technology (IT) in the past 20 years has prompted interest in the implications of IT for employment levels, workplace skill demands, and earnings levels and inequality. This interest has centered on a number of questions:

- Does IT eliminate more jobs than it creates?
- Is there a shortage of IT professionals?
- Does the spread of computers explain the significant growth in wage inequality in the United States in the past 20 years by altering the occupational distribution of employment and/or the skill content of occupations themselves?

Periodically, fears arise that automation will lead to mass unemployment. These fears find little support in available data, which show robust and nearly uninterrupted growth in employment between 1948 and 2000. During the boom years of the late 1990s, when IT penetration of the economy was greater than ever before, the nation's overall unemployment rate fell to its lowest levels in 30 years.

Some have expressed concern over perceived shortages of IT professionals. Although spot shortages would not be surprising in the booming technology sector of the late 1990s, researchers disagree as to whether a genuine shortage existed. In addition, because the share of IT professionals as a percentage of the overall workforce is relatively small, any such shortage would have only a limited effect on the general labor market.

The greatest concern raised in recent academic studies over the effect of IT is its possible contribution to the growth in earnings inequality observed since the late 1970s. The theory of *skill-biased technological change* (SBTC) argues that computers have increased the demand for skill in the general workforce and created a more broadly felt skills shortage, bidding up the relative wages of the more skilled. The theory remains controversial because others believe that different structural and institutional factors have played a larger role in increasing earnings inequality than demand shifts or a shortage of human capital.

The precise means by which computers might increase job skill requirements and earnings inequality is debated even among advocates of the SBTC theory. Computers can increase the skill demands within occupations in several ways:

- Learning to operate the equipment and software may require scarce skills, which increases the wage gap between more- and less-educated workers (*computer-specific human capital*).
- Because a computerized workplace involves the manipulation of symbols and information, employers may demand more conceptual, abstract reasoning, and

problem-solving skills of their workers. This development might also encourage employers to restructure work in ways that broaden job duties and give these employees more autonomy and decision-making responsibility (*general human capital—computer users*).

- Computerization within an organization may increase skill requirements and wages even for jobs that do not involve directly working with computers because of organization-wide changes in practices that result from computerization (*general human capital—computer users and nonusers*).

Computers can also increase the demand for skill and relative wages by altering the distribution of workers between occupations. This can occur by stimulating the growth of high- and medium-skilled jobs—not only the IT professionals who manage the technology, but also accountants and production planners who analyze the information it generates—or by automating less-skilled jobs out of existence, such as data entry clerks.

A large body of literature explores each of these possible causal pathways. Although many studies support the SBTC theory, others find the evidence for skill-biased technological change fragile and dependent on strong assumptions. Much has been learned about the diffusion of computers and IT and the pattern of wage inequality growth, but their possible interrelationship remains unclear and contested.

Chapter 1: Introduction

The rapid and widespread diffusion of computers and information technology (IT) at the workplace is one of the most notable trends of the past 20 years. This development has prompted both a great deal of excitement that IT might serve as an engine of growth and prosperity and also great concern that its effects on employment and job skill requirements have increased economic inequality. Many feel that IT is the hallmark of an Information Revolution as far-reaching as the Industrial Revolution of the previous century, with profound consequences for employment, earnings, well-being, and the economy and society in general even as debate and uncertainty continue over its exact implications. This report reviews principally the economics literature on the relationship among computers and related technologies; employment, skill, and wage levels; and inequality, drawing on other fields when technology and wages, human capital, or employment are discussed. Some significant related work is beyond the scope of this project, including important sociological literature on technological change and the deskilling of jobs as well as studies of the connections among technological change, changes in organizational structure (often referred to as "postbureaucratic" organizations), and social institutions (except as they relate directly to changes in workers' skills and wages). Additional research focusing only on IT's implications for organizational structure is outside the scope of this report (for a review, see Brynjolfsson and Hitt 2000).

This review primarily focuses on three principal questions:

- Does information technology eliminate more jobs than it creates, even leading, as some fear, to mass unemployment?
- Does a shortage of IT professionals exist?
- Does the spread of computers explain the significant growth in wage inequality in the United States in the past 20 years, either by:
    - ⇒ changing the character or *skill content* of occupations through various mechanisms, regardless of changes in the distribution of workers across occupations; or
    - ⇒ changing the *occupational composition* of employment through differential worker displacement and job creation processes, even if there is no impact on overall labor demand?

The rest of this review discusses historical, theoretical, and methodological issues involved in these debates and then addresses these questions in order, with particular attention given to the literature on whether IT has significantly increased the demand for skill and caused the recent increase in U.S. earnings inequality, known as the theory of *skill-biased technological change* (SBTC). In principle, the shortage of IT professionals might be considered an aspect of the changing occupational composition of employment, but in practice advocates of SBTC have made a much broader argument about the changing occupational structure and the two issues have been debated on separate tracks.

Chapter 2: Historical Perspective

Technological change is not new. Both manufacturing and nonmanufacturing industries have been the subject of dramatic technological change over time. The Industrial Revolution eliminated many traditional occupations in textiles, and subsequent changes in production technologies continued to alter the job content and occupational structure of all industries long before the emergence of computer technology. In perhaps the most dramatic example, roughly 38 percent of the U.S. labor force was employed in agriculture in 1900, but only about 6 percent were employed in that sector by 1960, and that figure has since stabilized at about 2 percent as a result of mechanization and other technological innovations (Handel 2000).

Concern over technology's impact is also not new. As early as the 18th century, economists and other observers debated the implications of new technology for employment and economic well-being (Woirol 1996, pp. 17 ff.). Although the contemporary perception is that the changes associated with IT are unprecedented, the real question is not the fact of change but the relative magnitude, speed, and consequences of that change compared to prior patterns of change. Some perspective on the current situation can be gained from understanding previous concerns regarding employment and technological change.

The first modern debate over the effects of technology occurred just before and during the Great Depression. The publication of the first firm government productivity data in 1926–27 showed both unexpectedly rapid gains and declining employment in certain manufacturing sectors. The recession of 1927 heightened concern in the popular press about a possible association between increased productivity and declining employment, but the Depression greatly magnified such concerns (Woirol 1996, pp. 23 ff.). Economists conducted case studies of plants or industries to understand the fates of workers displaced by technology, usually in manufacturing, often finding extended periods of unemployment and income loss for affected workers even during the 1920s, but the data did not permit generalizing from these cases to the economy as a whole (Woirol 1996, pp. 30 f., 48 f.). Other economists performed simple statistical comparisons of trends in output, employment, and productivity in different manufacturing industries to determine whether a connection existed between improvements in efficiency and declines in employment. Prior economic theory suggested that the efficiencies resulting from technology would generate sufficient demand to reemploy those displaced, but economists agreed that data and methodological limitations made impossible any real understanding of the extent to which technology did or did not tend to produce an ever-growing pool of persistently unemployed, as distinct from other factors such as trends in firm-specific or aggregate demand (Woirol 1996, pp. 47 ff., 75 f.). A number of government-sponsored commissions investigated the problem during the Depression but also failed to reach a consensus (Woirol 1996, pp. 62 ff.).

Quite rapidly, World War II transformed the slackest labor market in U.S. history into the tightest, and the issue of technology-generated unemployment disappeared from both popular discussion and empirical study among economists (Woirol 1996, p. 69). Following World War II, both excitement and concern over technology revived because of both technological advances and cyclical fluctuations in unemployment. About this time the term *automation* was coined to describe new, self-acting manufacturing technology, such as the automatic feeders and unloaders introduced in a Ford Motor Company engine plant. In the 1950s, reports emerged of oil refineries and chemical plants that replaced batch production with continuous process technology and reduced labor requirements to only five to seven workers who monitored dials, recorded numbers, and performed troubleshooting tasks. As many as a thousand designers and manufacturers of industrial equipment were in the automation field by 1955, and new trade journals appeared. In the early 1950s, the popular and business press began to speak of the possibility of a fully automatic factory. Concern was muted initially, but the recession following the Korean War and associated unemployment led some to draw a connection between job loss and the excitement over automation (Woirol 1996, pp. 77 ff.; and Bix 2000, pp. 240 ff.).

In the service sector, the introduction of direct-dial service for local telephone calls eliminated the need for vast numbers of operators to perform switchboard connections, but the dramatic expansion of service meant that overall employment at AT&T increased, and large numbers of operators were still required to perform other functions. Computers allowed an insurance company, studied by the Labor Department in 1955, to reduce its central clerical staff from 198 to 85, but nearly all of those displaced were transferred to other jobs within the company with the same earnings, and most of the rest left through natural processes of attrition during the 2-year transition period. Similarly, around this time Bank of America introduced magnetic ink character recognition technology that made it possible for machines to sort checks, track transactions, and print statements with just 9 operators instead of 50 bookkeepers, according to one account. Other scanning technology was in development at the time, raising the possibility of a virtually paperless operation that would render typists, clerks, and bookkeepers obsolete, but Bank of America anticipated that the consequent expansion of the business would allow existing employees to be transferred to other positions (Bix 2000, pp. 242 f., 275).

Some viewed the contemporary enthusiasm surrounding automation as hyperbolic, but others were concerned about the possibility of widespread layoffs and technological displacement, leading Congress to hold hearings on the subject in the late 1950s. Labor leaders expressed concern over whether growth could keep pace with technological advances to ensure the reemployment of displaced workers and whether older workers could be easily retrained. Business executives argued that increased efficiency would generate growth sufficient to absorb any workers whose jobs were eliminated and that the technology itself would require more highly skilled maintenance workers and create new occupations, such as technicians and computer programmers. The Bureau of Labor Statistics conducted case studies of automation's effects in particular offices and factories. The resumption of output and employment growth in the mid-1950s caused this debate to be less heated than similar debates during the Depression (Woirol 1996, p. 164; and Bix 2000, pp. 243 ff.).

However, concern revived between 1957 and 1964, when the economy slowed and unemployment increased sharply and remained stubbornly high (see figure 2). John F. Kennedy ran for president on a platform of revitalizing the economy and gave the issue prominence. He created an Office of Automation and Manpower in the Labor Department in 1961; appointed a high-level commission to examine the issue; and enacted an education and retraining program for displaced workers, the 1962 Manpower Development and Training Act (Woirol 1996, pp. 77 f.; and Bix 2000, pp. 258 ff.). In 1962, Kennedy identified "the major domestic challenge of the Sixties—to maintain full employment at a time when automation, of course, is replacing men" (Woirol 1996, p. 96).

In labor relations, a national rail strike was narrowly averted in 1963 over complaints by owners that unions were featherbedding by requiring that crews continue to use firemen to stoke boilers even after the switch from steam to diesel. A typographers' strike shut down New York's publishing industry for nearly 4 months that same year in a dispute over new typesetting equipment. In 1964, the New York longshoremen's union, anticipating the effects of cargo containerization and mechanization on labor demand, won a guaranteed income for senior members regardless of the need for their services; indeed, the number of longshoremen moving cargo for the New York–New Jersey ports declined by 75 percent between 1966 and 1975 even as the tonnage of cargo handled increased more than 20 percent. As one longshoreman recalled, "Automation just killed us." The business and popular press weighed the promise and perils of automation, with some predicting that, by the early 1980s, computers would perform all jobs except for the work of technicians required to operate them. In 1963, the Senate held hearings on the "Nation's Manpower Revolution" to consider the issue (Woirol 1996, pp. 84, 95 f., 100; and Bix 2000, pp. 259 ff., 270).

Around this time economists coined the term *structural unemployment* to describe involuntary unemployment that did not reflect the business cycle or traditional patterns of temporary job loss or search. Structural unemployment was believed to be concentrated in particular occupations, industries, or regions as a result of long-term shifts in the economy, such as changes in production technology or consumer spending patterns. Others added nonwhites, women, and young people to the groups experiencing structural unemployment. In 1962, advocates of the structural unemployment concept articulated a new technology acceleration hypothesis that would be recognizable to contemporary proponents of skill-biased technological change theories: increasingly rapid technological change such as automation created a significant barrier to absorbing segments of the unemployed by accelerating the shift in labor demand toward more-skilled and white collar workers. Charles Killingsworth testified at the 1963 Senate hearings that "automation appears to be spreading more rapidly than most major technological changes of the past" and that "the fundamental effect of automation on the labor market is to 'twist' the pattern of demand—that is, it pushes down the demand for workers with little training while pushing up the demand for workers with large amounts of training" (Woirol 1996, pp. 103 f.). He noted that it was the unemployment and labor force participation rates of noncollege-educated males that showed the most significant deterioration between 1950 and 1962 and consequent evidence of labor surplus, as advocates of SBTC would later argue was the case in the 1980s and 1990s. Others questioned the quality of the data and analyses on which these conclusions were based (Woirol 1996, pp. 104 ff., 121).

Proponents of the structural unemployment concept argued that reducing overall unemployment would be insufficient to assist these groups and that more targeted programs were needed to address the mismatch between existing job vacancies and those unemployed or out of the labor force who, for various reasons, were unable to take advantage of them. However, a debate soon developed as a more prominent group of economists argued that the problem was simply slow growth and that fiscal and monetary policies that lowered aggregate unemployment by stimulating demand would be sufficient to absorb the less-skilled and other disadvantaged workers. This group favored the administration's 1964 tax cut, an early and well-publicized effort to consciously manage the economy through fiscal policy (Woirol 1996, pp. 79 ff., 95, 97 f., 100 ff.).

In 1965, President Lyndon Johnson appointed a National Commission on Technology, Automation, and Economic Progress, which concluded that the main cause of high unemployment was slow economic growth, not technological change. However, by the time the report was issued, the point was moot; economic growth had resumed in earnest. By 1965, the tax cut and growing government spending led to a sharp decline in unemployment and a booming economy for the rest of the decade. Popular and academic concern with automation and structural unemployment largely evaporated, repeating the experience of the Depression and World War II periods (Woirol 1996, pp. 111, 127).

In both the 1930s and early 1960s, popular concern helped fuel government inquiries and professional debates, but most economists believed that the problem of technology-induced unemployment had been overstated in both cases, although others took a contrary view. In both cases the debate faded not because of convincing research findings or expert consensus but because of increased economic activity (Woirol 1996, pp. 8 f.).

As in previous periods, the deep recession of the early 1980s prompted concerns over the effects of new technology, leading a joint committee of the National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine to create the Panel on Technology and Employment. The panel examined the effects of technology on overall employment levels, job displacement, the occupational distribution of employment, skills, wages, and emerging training and education requirements (Cyert and Mowery 1987, pp. 209 f.). The panel concluded that technology is a modest contributor to job loss, skill upgrading, stagnant earnings, and inequality growth and cited slow economic growth and perhaps trade as more likely culprits (Cyert and Mowery 1987, pp. viii, 60 f., 86). The panel noted the existence of similar fears about the effects of technology during the Depression and the late 1950s–early 1960s period and how they faded when full employment returned (Cyert and Mowery 1987, pp. 87 ff.). The overview of the technical papers accompanying the report acknowledged that the evidence on the effects of new technology on employment and skills is "extraordinarily weak" (Cyert and Mowery 1988, p. xxxiii).

The historical record reminds us that, in some sense, we have already been here before. Anxiety and sweeping claims about the effects of technology are not new, although they have often been undersupported with evidence and, in retrospect, exaggerated.

In both earlier debates, there was a strong tendency to confuse technological displacement with weakness in overall demand, which is also known to affect less skilled workers most severely. The early mechanization/automation controversies and the high unemployment rates that occasioned them faded from view considerably when the business cycle reversed and growth resumed. Clearly, technology is only one of many variables affecting employment and the labor market, and it is not at all obvious that it is as significant as macroeconomic conditions. However, this does not negate the possible hardships experienced by disadvantaged groups or those adversely affected by structural changes in the economy, even during periods of expansion, who may require targeted efforts such as retraining, job placement assistance, or extended support.

This qualification implicitly recognizes—and the case studies of worker displacement in both the 1920s–30s and 1950s–60s confirm—that technology is a genuine force for change in the labor market that cannot easily be dismissed. However, by the same token, these cases remind us that similar examples of technology-induced change that could be cited today are not unique and, insofar as these case studies are compelling evidence of technological effects in the past, they beg the question as to what is distinctive about more recent developments. Case studies are vital for understanding concrete processes and mechanisms of change in a way that statistics fail to capture, but it is difficult to generalize from them or use them to construct historically consistent indexes of technological impacts either within or across industrial sectors. Case studies cannot answer questions about whether the pace of technological change and its effects have accelerated over time. At best, case studies are only suggestive evidence of historical variations in the pace of technological change.

One of the most notable features of previous debates was the weakness of the empirical evidence on both sides. At no point in either debate could anyone determine precise levels of technological unemployment beyond individual cases or anecdotes, nor could anyone separate the effects of technology from potentially unrelated changes in aggregate or firm-specific demand; however, that did not prevent participants from drawing strong conclusions (Bix 2000, pp. 242, 245, 256). When debates ended it was not because theory or data resolved them; interest simply faded when economic conditions improved (Woirol 1996).

Chapter 3: Conceptual Issues: Theory, Methods, and Nature of Information Technology

Theoretical Perspectives

Many of the issues raised in previous debates are still relevant to an examination of IT's relationship to the workforce. The effects of computer technology on employment must be distinguished from the effects of the business cycle, fluctuations in firm-specific demand, and other changes that may be unrelated to technology, such as growth in imports and offshore production. If IT represents an unprecedented economic development, one must show not only change but also an accelerated pace of change relative to the past. Similarly, the quality of the evidence remains an important concern.

For present purposes, IT can influence labor markets in three ways: it can affect the total number of jobs regardless of skill level or occupation, it can alter the skill mix of jobs through changes in occupational demand, and it can alter the skill mix of jobs through changes in the skill content of occupations without necessarily changing the occupational distribution.

A great deal of public concern has always focused on the question of whether technology is eliminating the need for human labor in general. The most extreme version of this idea argues that the future economy will require virtually no workers, causing massive unemployment and idleness (Aronowitz and DiFazio 1994; and Rifkin 1995). This concept implies a somewhat paradoxical vision of an economy so efficient that it has no way to distribute its abundant output because everyone is out of work; it is hard to see how businesses could continue to produce vast quantities indefinitely in the absence of paying customers (i.e., earners). A more modest version of this idea, with greater support among economists, holds that technology may result in a more limited net job loss or persistent job shortage, in which a certain fraction of the labor force faces long-term unemployment even when the economy is expanding. This issue of "jobless growth" has received some support and attention in the Western European experience (OECD 1996, pp. 62, 68).

The principal objection to the thesis of a jobless future is that technology-induced efficiencies lower prices and give consumers more wealth, which they can use to increase their consumption of goods or services, including those whose price has dropped. In this case, increased productivity translates into increased output and employment, assuming that producers do not have monopoly power to maintain prices and reap all the gains from these improvements and that consumers increase consumption rather than save their new wealth. Expansion in the industries responsible for the new labor-saving technologies (e.g., computers) will also increase employment (OECD 1996, p. 9 ff.; and Cyert and Mowery 1987, pp. 1 f.).

The problem with this view is that there is no reason in principle why the number of jobs created would necessarily fully offset those that are lost. However, most economists derive some confidence from the empirical record, which generally has not supported the more extreme predictions of technological unemployment that have been advanced since the Industrial Revolution.

However, even those who do not believe that IT poses a threat to overall employment recognize that there is less reason to assume that labor-saving efficiencies will be exactly balanced by increased labor demand for particular categories of workers. If consumers use money saved from price declines in one industry to buy goods or services provided by another industry, the jobs created may be very different from those that are lost, and some workers may suffer the kind of structural unemployment described previously. If labor demand does fall for some groups, employment levels can be maintained only at the cost of lower wages (OECD 1996, pp. 10 ff.). Thus, technology may not dramatically reduce overall labor demand, but it may alter the composition of employment or the type of labor demanded.

Some believe that this describes recent trends in employment and wages. Wage inequality has grown dramatically in the past 20 years, and many economists believe that computer technology has played a significant role in this process by reducing demand for less-skilled workers, some of which is manifest in declining employment for the less skilled (Katz and Murphy 1992; Krueger 1993; Berman, Bound, and Griliches 1994; Danziger and Gottschalk 1995; and Autor, Katz, and Krueger 1998). Proponents of this view argue that computer technology is skill biased rather than skill neutral. The skill-upgrading effects of computers are not intrinsically problematic—they promote less physically demanding and more mentally challenging work—but the theory of skill-biased technological change (SBTC) states that the pace of change is so rapid that the demand for skill has outstripped the ability of the labor supply to meet it and has widened wage differentials.

Although economists generally do not frame the issue this way, the nature of the evidence makes it useful to distinguish two ways computers may increase the demand for skill (for an exception, see Howell and Wolff 1991). Computers can affect the occupational composition of employment by either eliminating low-skilled jobs through automation or increasing the number of medium- and high-skilled jobs, such as computer programmers or white collar workers, needed to analyze the increased number of reports that a computerized workplace generates. Alternatively, computers may increase the skill content of an occupation—for example, if IT is difficult to learn or requires greater abstract reasoning abilities—without necessarily altering that occupation's share of the workforce. These two mechanisms—changes in the occupational composition and the skill content of occupations—will be referred to as *between-occupation* and *within-occupation* effects (Spenner 1983, 1979). The distinction is important because different studies address one or another of these processes under the common rubric of "skill-biased technological change" without mentioning that they are making different assumptions about causal mechanisms with distinct evidentiary requirements. In particular, data on between-occupation effects are more readily available than for within-occupation effects, and one should be aware of the data's limitations. However, the distinction is also a useful way to clarify the concrete mechanisms whereby computers may affect skill demands. Thus, there are three principal questions for this review:

- Does IT eliminate more jobs than it creates, even leading to mass unemployment?
- Does IT increase the demand for skill by changing the occupational composition of employment through differential worker displacement and job creation processes, even if there is no overall effect on labor demand?
- Does IT increase the demand for skill by changing the character or skill content of occupations, regardless of changes in their relative proportions?

Methodological Issues

Three serious methodological issues impede deeper understanding of IT's impact on work and the labor market.

First, measures of information technology are imperfect. Before the 1980s, most measures of any kind of technology were indirect, such as productivity, the value of capital invested, the level of spending on research and development, and the percentage of scientific and technical personnel or the percentage of nonproduction workers in an industry. One exception is the time series for investment in office, computing, and accounting machinery and computer investment in manufacturing produced by the U.S. Department of Commerce, which has been used for a few studies (Berman, Bound, and Griliches 1994; and Autor, Katz, and Krueger 1998). Beginning in 1984, the Bureau of Labor Statistics' Current Population Survey (CPS) also periodically asked employees about computer use at work, but the results of research using these data have proven controversial. Other direct measures of information technology, such as factory automation, are even more scarce (Doms, Dunne, and Troske 1997).

Second, even when measures of information technology appear reasonable, great difficulty exists in drawing firm causal inferences between trends in IT on the one hand and trends in employment, skills, and wages on the other. Problems include potential spuriousness owing to omitted variables that affect both the presence of IT and employment characteristics, difficulty distinguishing cause from effect and possible two-way causation, and various empirical anomalies.

Third, other than broad occupational categories, there are few direct measures of job skill requirements besides those derived from the *Dictionary of Occupational Titles* (DOT), published by the Employment and Training Administration of the Department of Labor in 1977. Most of the DOT job ratings were collected in the late 1960s and 1970s and can be used to measure between-occupation effects after merging them with Census or CPS data. In the absence of more recent ratings, there is no way to trace trends in the skill content of occupations over time or correlate them with trends in computer use, so investigating potential effects of IT within occupations for a national sample is problematic. Trends in education and wages have been used as indirect measures of job skill demands, but a job holder's education is a personal characteristic, not a direct measure of job complexity, and wages are potentially affected by variables other than skill shifts, such as international trade, unionization, the minimum wage, and macroeconomic conditions.

These limitations of data and method, as well as the ambiguities of certain results, contribute to the debates over the effects of IT on the labor market.

A Brief Description of Information Technology

Although many economists use the term *technology* to refer to any aspect of the organization of production, this review uses a narrower and more intuitive definition. Information technology, or IT, refers to capital equipment that makes extensive use of microelectronics and programmed instructions or software. A number of distinct characteristics are often associated with IT, although not all apply to all hardware and software. IT systems are frequently fast, precise, high storage, high capacity, highly flexible, reprogrammable, and automatic or self-acting. They may be able to record, process, communicate, and react to information from users and feedback from the environment in more or less sophisticated ways. Many systems have only a subset of these abilities, but the novelty and power of these characteristics are undoubtedly a large part of the reason for the attention and excitement over IT.

Prominent examples of IT specific to manufacturing, repair, and similar blue collar environments include numerically controlled and computer numerically controlled machine tools; robots; computerized diagnostic and testing equipment; onboard computers in automotive vehicles; automated telecommunications switching equipment and controllers; sensors; manufacturing process controls, such as programmable logic controllers; automated material handling equipment; automated inventory and parts storage and retrieval systems; automated guided vehicles; computers for monitoring, analyzing, and controlling industrial processes; factory local area networks (LANs); computer-aided design and manufacturing (CAD/CAM); material resource planning software to manage supplies and inventory; and flexible manufacturing systems that integrate automated machining, material handling, and delivery systems (Doms, Dunne, and Troske 1997; Zuboff 1988, pp. 418 ff.; and Siegel 1999, pp. 46 ff.).

Prominent applications of information technology in office and service-sector environments include common desktop software such as word processors, spreadsheets, databases, e-mail clients, and Internet browsers; personal digital assistants and other handheld devices; videoconferencing and distance learning technologies for training and education; onboard computers in police vehicles and trucks for information exchange and remote database access and monitoring; data entry and transactions processing systems (e.g., payroll, billing, bank transactions, and insurance claims); other forms of record management (e.g., medical records); paper sorting systems (e.g., mail sorters); computer programming; LANs; CAD; graphic design and printing; automated teller machines; bank networks for electronic funds transfer; electronic data interchange for automated ordering and payment between purchasers and suppliers; barcode scanners; point-of-sale devices; and inventory management devices and software.[1]

Clearly, computer and microelectronic technologies have developed diverse applications, some of which save more labor or require more skill to use effectively than others. Any consideration of the effect of information technology on the labor market ultimately rests on some plausible account of the effects of these specific and similar systems on the number and types of workers they displace and on the skill requirements for operating them or working in a computerized environment.

When considering IT's impact, product complexity must be distinguished from process complexity. Most people who use electric devices or drive automobiles do not have a sophisticated understanding of their underlying principles. The fact that the equipment is sophisticated does not mean that all processes that involve interfacing with that equipment require high levels of skill. The manufacture of complex products, such as computers, may require minimal skill in some labor-intensive stages, such as final assembly, and may require minimal skill to operate in certain contexts, such as data entry. Whether high-technology equipment is associated with high-technology or highly skilled jobs is an empirical question.

[1] These examples are largely independent of the additional examples that could be cited of embedded microchips found in many other devices, such as electronic cash registers or videocassette recorders, which are not computer systems in the same sense as the others listed.

Chapter 4: The Public's Views of Information Technology's Impact on Work

The attitudes of workers and the general public toward IT's effects on employment may or may not reflect personal experience with technology in the workplace, but they are important for understanding popular concerns regarding the issue. These attitudes are often positive, but they also include concerns about societal impacts and other problems among those personally affected.[2] As will be clear, most of the questions deal with concerns about job loss rather than skill shifts.

As early as 1965, a Harris poll revealed that more than half of the respondents believed that automation raised unemployment rates, whereas 38 percent thought it resulted in better and cheaper consumer goods. Among skilled and unskilled blue collar workers, 14–16 percent felt at risk of job loss because of automation, whereas only 4 percent of managerial and professional workers thought similarly (Bix 2000, pp. 273 f.).

As table 1 indicates, the Survey of Working Conditions (1969) and the Quality of Employment Survey (1972–73) found that, about 30 years ago, 16–22 percent of workers believed that machines and computers were at least somewhat likely to perform many of their job tasks in the next few years, but only about 15 percent of those workers (about 3.5–5 percent of all workers) anticipated that this would result in job loss rather than continued employment in their current position or internal transfer (Handel 2000).

A Roper poll (1980) found that 72 percent of adults thought that computers had made life at least somewhat better, and only 23 percent felt that computers had any negative effects. In the same poll, 30 percent said that computers keep prices down and "free workers from drudgery and give them more time to do creative things," but even in 1980, 38 percent thought that "too many people had lost their jobs because they have been replaced by computers."

In a sample of registered voters responding to a Time/Yankelovich poll (1982), 52 percent thought that computers "will throw a lot of people out of work" and 51 percent thought that they will "take a lot of satisfaction out of jobs."

When asked in a Harris poll (1984) about "the increased use of information-processing systems, such as computers or word processors," 43 percent of adults said that they will worsen unemployment and 50 percent said that they will help create jobs.

[2] Unless otherwise noted, these poll results are derived from the Roper Center for Public Opinion Research database of survey data, available through the Lexis-Nexis Internet database service. Precise question wording and tabulations of responses are available from the author.

Table 1. Percentage of Workers at Risk for Job Loss Due to Technology: 1969 and 1972–73

	1969	1972–73	1969	1972–73
Probability of Technology Impact [1]				
Very likely	8.0	9.7		
Somewhat likely	8.0	12.0		
A little likely	9.9	11.1		
Not at all likely	74.2	67.2		
N	1, 320	1, 268		
	All		***At Risk Only*** [3]	
Consequences [2]				
Out of job	3.5	4.7	14.2	14.6
Other job, same employer	9.0	11.7	36.3	36.5
Job adapted to machine	11.8	15.4	47.4	48.4
Other	0.5	0.2	2.2	0.5
Not affected by technology	75.2	68.1	--	--
N	1, 311	1, 254	325	390

Source: Survey of Working Conditions (1969), Quality of Employment Survey (1972–73). Figures for 1972–73 use sample weights; those for 1969 are self-weighted. From Handel (2000).

[1] Based on responses to question: "How likely is it that in the next few years, machines or computers will be doing a lot of the things you now do on your job?"
[2] Based on responses to question, "If this happens, would you be out of a job, or would your employer find something else for you to do, or would your job just be adapted to the machine or computer, or what?" Small percentage responding "don't know" excluded.
[3] "At risk" excludes those responding "Not at all likely" to previous item.

A Roper poll (1986) found that 54 percent of adults thought the use of industrial robots on assembly lines should be "severely limited," whereas only 21 percent thought they should be "greatly expanded." In the same poll, 63 percent thought that if robots were used, unemployment would increase and retraining would not be sufficient to address the problem. Similar questions asked during a recession year (1982) elicited responses that were about 10 percentage points more negative.

A Gallup poll (1989) found that 52 percent of adults thought that robots would replace most assembly line workers by the year 2000.

The 1998 General Social Survey conducted by the National Opinion Research Center asked respondents whether new types of technology such as computers and robots will increase or decrease the number of jobs over the next few years and whether new technology will make work more interesting. Tables 2 and 3 suggest that about 50 percent think that IT will reduce employment to a greater or lesser degree and about 40 percent think that IT will increase employment, but nearly 70 percent think that IT will make work more interesting (author's calculations).

Table 2. Effects of Computers, Robots, and Other Technology on the Number of Jobs in Next Few Years: 1998

Greatly increase	16.47
Slight increase	21.42
No difference	11.61
Slightly reduce	29.61
Greatly reduce	20.88
N	1,111

Source: General Social Survey (1998). Author's calculations.

Table 3. Will New Technologies Make Work More Interesting in Next Few Years: 1998

Much more	31.27
A little more	36.83
No difference	20.07
A little less	7.80
Much less	4.03
N	1,116

Source: General Social Survey (1998). Author's calculations.

A 1999 survey sponsored by National Public Radio, the Kaiser Family Foundation, and Harvard University's Kennedy School of Government found that 87 percent of adults under 60 thought computers were making life better for Americans. About a third believed computers in the workplace would decrease the number of available jobs (see table 4), but only 13 percent were concerned they might lose their own job in the future as the result of technological advances (5 percent were very concerned)—numbers remarkably similar to those in the Survey of Working Conditions (1969) and Quality of Employment Survey (1972–73) (see table 1). By contrast, 43 percent thought computers would increase employment and 23 percent thought they would not make much difference. About 40 percent thought computers would increase wages and 20 percent thought they would decrease wages, while another 40 percent thought they would make no difference (see table 4). However, 45 percent said they thought computers widened "the gap in income and opportunity between the haves and have-nots in our society," whereas 11 percent thought computers narrowed the gap and 39 percent thought they made no difference (National Public Radio, Kaiser Family Foundation, and Kennedy School of Government 2000, pp. 20 ff.).

Table 4. Effects of Computers on Employment and Wages: 1999

	Increase	Decrease	No difference
Employment	43	32	23
Wages	39	19	39

Source: National Public Radio, Kaiser Family Foundation, and Kennedy School of Government 2000, p. 22.

Although the survey record suggests a significant division of opinion between those who are generally optimistic and those concerned about possible job displacement, only about 15 percent of respondents believe their own jobs are at risk, a figure that appears to have remained stable over the past 30 years.

Chapter 5: Technology and Trends in Overall Employment

As noted previously, predictions that technology would lead to the wholesale elimination of jobs and mass unemployment have persisted for many years, particularly during the automation debates in the late 1950s and early 1960s. Few academic economists take such predictions seriously, partly because of the theoretical reasons discussed earlier and partly because of the U.S. record of employment growth. Nevertheless, this prediction regained attention recently in the context of the dramatic spread of computers, which led some to claim that high technology destroys more jobs than it creates and that employment growth is not sufficiently rapid to offset this displacement (Aronowitz and DiFazio 1994, pp. 1 ff., 21).

Although he does not cite specific figures, Jeremy Rifkin, writing in the mid-1990s, described the economy as being in a "jobless recovery" in which continued layoffs and downsizing and increased numbers of permanently displaced workers foreshadowed "massive unemployment" and a "near workerless, information society" (Rifkin 1995, pp. xv ff., 5, 59). Although most economists would find this view exaggerated, two prominent trade economists, Paul Krugman and Robert Lawrence, claim that "the concern, widely voiced during the 1950s and 1960s, that industrial workers would lose their jobs because of automation, is closer to the truth than the current preoccupation with the presumed loss of manufacturing jobs because of foreign competition" (quoted in Rifkin 1995, p. 8).

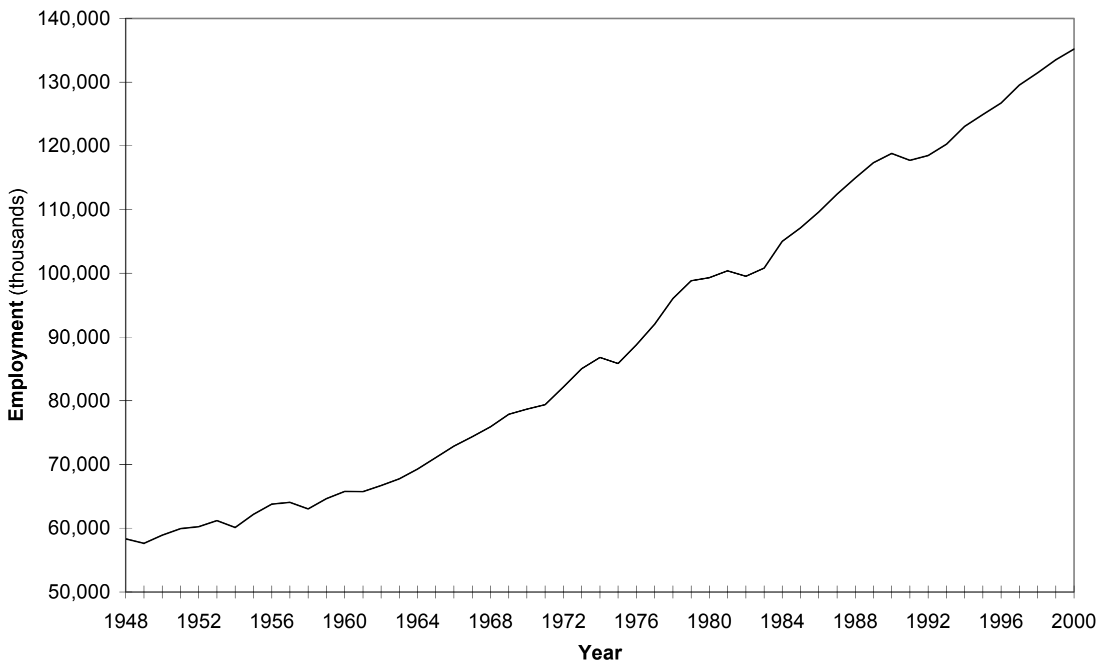
Rifkin argues that the full displacement effects of automation during the 1950s and 1960s were suppressed by government spending on military, public works, and social programs and the introduction of new consumer products and services, all of which maintained demand and reabsorbed labor. In his view, limits on government spending and restructuring and automation in service industries mean that there will be no similar source of labor demand in the future, and employment in IT industries themselves will remain too small to compensate for the displacement that will result. Rifkin comes closer to the structural unemployment view when he argues that remaining jobs will have high educational requirements that limit the retraining and reemployment possibilities for workers displaced from less-skilled blue collar and white collar jobs (Rifkin 1995, pp. 32 ff.).

Although it is hard to disentangle all of the variables Rifkin invokes, some perspective on the question of "the end of work" can be gained by examining trends in employment.[3] Figure 1 shows that between 1948 and 2000, total employment more than doubled from less than 60 million workers to more than 135 million workers, with some

[3] All data are from the *Economic Report of the President* (Executive Office of the President 1989, 2000).

sign of a modest acceleration since 1970. These numbers give no indication of a jobless or workerless economy. These statistics do not adjust for declines in hours worked since World War II, but there is general agreement that most of this decline ceased by the early 1970s and represented a gain in leisure time for workers that most viewed as a benefit rather than as a form of involuntary underemployment (Schor 1991).

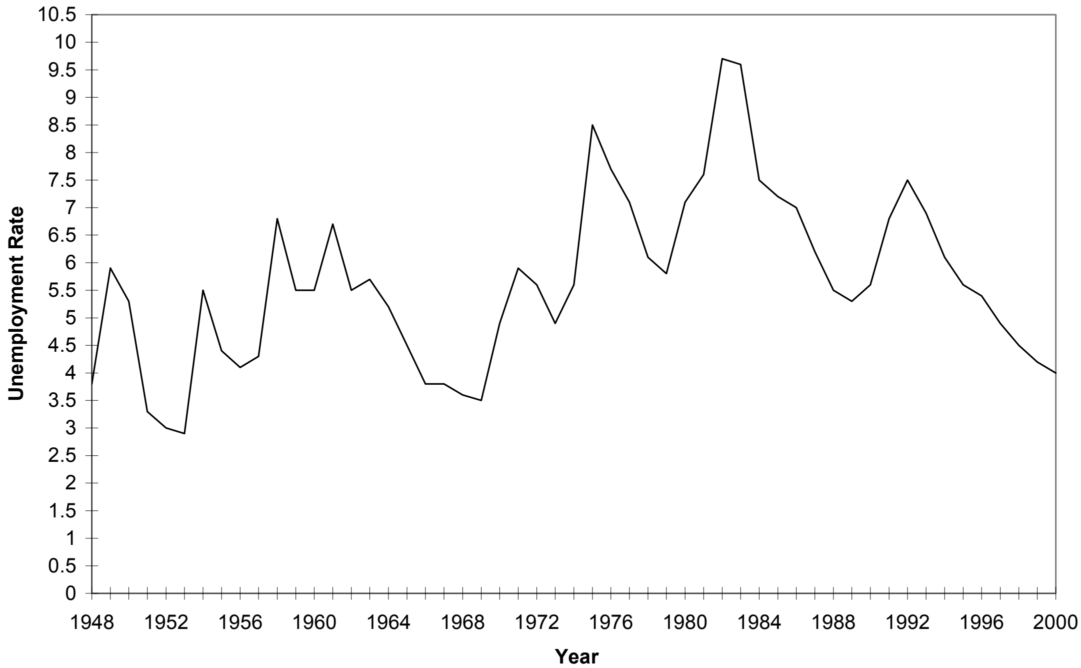
Figure 1. Total Employment: 1948–2000



Source: *Economic Report of the President* (1989, 2000), Washington, DC: Government Printing Office.

Even if the number of jobs is not falling in an absolute sense, a growing job shortage may exist relative to the number of job seekers. Figure 2 shows that the unemployment rate tended to rise to higher levels during each recession since the 1950s and remained relatively high during the 1970s and 1980s. However, the long expansion of the 1990s broke this pattern, and unemployment dropped steadily to its lowest level since the boom of the late 1960s. By 2000, unemployment was only 4 percent, a level bettered only in the 1951–53 and 1966–69 periods. Rifkin's (1995) prediction of massive unemployment appeared just as the economy drove unemployment to levels not seen in 30 years.

Figure 2. Unemployment Rate: 1948–2000



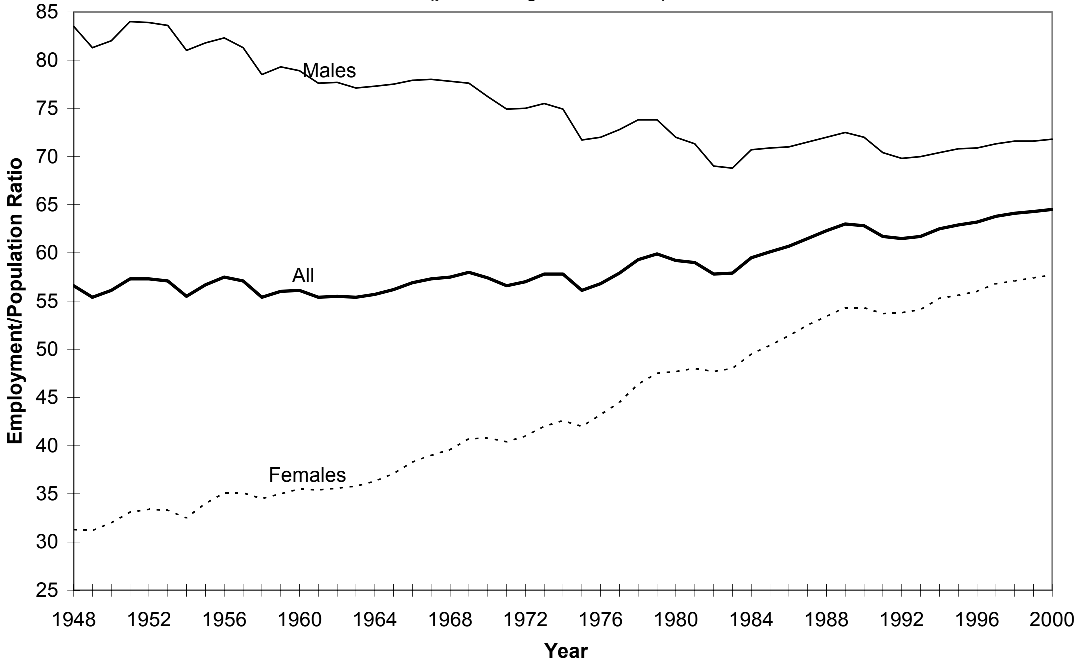
Source: *Economic Report of the President* (1989, 2000), Washington, DC: Government Printing Office.

Nor is it the case that declining unemployment merely represents withdrawal from the labor force among those displaced. Figure 3 does not suggest any dramatic declines in the employment/population ratio over time, except for the trend toward earlier retirement for men when incomes were rising, which few attribute substantially to technological displacement.

Contrary to Rifkin's assertion, some evidence indicates that IT as a share of total investment across seven OECD nations is positively related to total and service sector employment growth between 1985 and 1995, although other data suggest a negative relationship between productivity growth and manufacturing employment growth for a larger set of countries (OECD 1998, pp. 50 f.).

The economics literature on skill-biased technological change raises more serious concerns that the buoyant growth in overall employment masks employment declines for less-skilled workers. Some believe that the lower wages accompanying the lower employment rates among less-skilled workers are another indication of declining demand for these workers. If wages did not decline, employment would have fallen even more. Indeed, with the exception of the last few years of the late 1990s boom, the real wages of production and nonsupervisory workers has remained stagnant or declined slightly since 1973 after growing roughly 75 percent between 1947 and 1973 (U.S. Department of Labor 1999; and author's calculation from Executive Office of the President, *Economic Report of the President*, various issues).

Figure 3. Employment/Population Ratio: 1948–2000
(persons age 16 and over)



Source: *Economic Report of the President* (1989, 2000), Washington, DC: Government Printing Office.

Chapter 6: Trends in Demand for Information Technology Workers

Although the growing number of IT professionals might be the most obvious sign of the computer's effect on occupational distribution and the demand for skill, the research on skill-biased technological change (SBTC) and inequality has not specifically been concerned with IT workers. In fact, a number of researchers have been careful to specify that the SBTC thesis refers to IT effects that extend beyond IT occupations and industries (Autor, Katz, and Krueger 1998, p. 1186; Bresnahan, Brynjolfsson, and Hitt 1999, p.13, 2002; and Levy et al. 1999, p. 7).

However, good reasons exist for examining IT employment in particular. Traditional arguments against the technological unemployment thesis cite job gains in the industries supplying new technology as a way to offset employment gains, and employment growth in the IT sector has attracted popular attention. Employment gains for highly skilled workers and job losses for less-skilled workers within this sector may also illustrate some of the processes of SBTC, even if the full implications of this process require taking a broader view. Finally, during the late 1990s boom, many were concerned that the United States faced a shortage of IT workers, which stimulated a debate over relaxing limits on nonimmigrant work visas for engineers, computer scientists, and other highly skilled technology workers. Thus, although the issue is largely tangential to the academic debate over SBTC, employment and wage trends in the IT sector itself have attracted interest for a number of reasons.

In the late 1990s, most attention focused on concerns about a shortage of highly skilled IT workers. The Census Bureau has traditionally used two or three relatively broad categories to measure trends in these occupations. Tabulations using the Current Population Survey (CPS) indicate that the percentage of all U.S. workers who were computer scientists and computer systems analysts grew from 0.10 percent in 1971 to 0.35 percent in 1982 to 1.16 percent in 1997, whereas the corresponding figures for less-skilled computer programmers were 0.25 percent (1971), 0.47 percent (1982), and 0.56 percent (1997). Combined, these workers still accounted for less than 2 percent of total employment in 1997 (Handel 2000, p. 266).

Interestingly, although the percentage of computer scientists and systems analysts accelerated in the late 1980s, the share of programmers did not, perhaps because of the spread of prepackaged software, end-user programming (software features that allow users to perform operations that previously required programmers), improvements in program design, object-oriented programming using reusable modules of code, automation of code writing, and the use of offshore programmers, particularly from India and Ireland (*Occupational Outlook Quarterly* 1992; Stremlau 1996; U.S. Department of Commerce 1997, pp. 11, 16; Ó Riain 1997, 2000; U.S. Department of Commerce 1999, pp. 22, 27; and National Research Council 2001, pp. 63 f., 127). U.S. Department of

Labor projections confirm that the future expansion of programming jobs will be relatively slow and comparable to the growth rate of the workforce overall, although relatively high turnover rates in these jobs will create more vacancies than otherwise projected (U.S. Department of Commerce 1999, p. 26, 28).

Even allowing for the undercounting of some scientists, mathematicians, engineers, and technicians working in the computer hardware and software industries, highly skilled IT occupations still represent a relatively small part of total employment.[4] Any difficulty satisfying employer demand for IT workers must be considered a spot shortage rather than evidence of a more general problem.

Still, the industry is widely seen as pivotal to recent U.S. economic performance and receives considerable attention. In 1997, a survey of medium and large firms conducted by the Information Technology Association of America (ITAA) found that IT companies had about 190,000 unfilled IT professional jobs in 1996 because of a shortage of qualified workers; this shortage represented the most significant bottleneck for IT company growth (U.S. Department of Commerce 1997, pp. 3, 20; and Freeman and Aspray 1999, p. 15, 1997, pp. 3, 20). A similar ITAA study in 2000 estimated that 425,000 IT jobs went unfilled, but the study also defined IT workers somewhat more broadly than later discussions; it included more than 7 percent of the workforce, including those with primary training from proprietary technical schools and vendor certificate programs (www.itaa.org/workforce/studies/01execsumm.htm). Despite possible problems with the quality of the study, the initial ITAA report stimulated further study and debate.

A U.S. Department of Commerce study generally supportive of ITAA's concern found that the number of new computer science degrees awarded increased dramatically during the 1970s and especially between 1978 and 1986, rising from about 5,000 in the early 1970s to 50,000 in 1986 before declining somewhat in the late 1980s and flattening out to about 35,000 per year in the early 1990s. This stagnation raised concerns about the level of America's technical education (U.S. Department of Commerce 1997, p. 13; and U.S. Department of Commerce 1999, pp. 37 f.). Although this rate of degree production would seem to fall far short of the 190,000 vacancies anticipated by the 1997 ITAA survey, that study appears to define IT professionals more broadly than the Census Bureau defines them.

Another problem with linking the number of undergraduate computer science degrees awarded with the number of IT job vacancies is that only an estimated 31 percent of IT professionals actually have a degree in an IT field, although another 27 percent have a degree in another engineering, math, or science field, and many who have IT degrees do not work in IT occupations. Indeed, despite the decline in the number of IT degrees awarded since 1986, the employment of IT professionals nearly doubled by

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[4] Although the computer hardware industry employs workers at all skill levels, it has never accounted for as much as 1 percent of total employment, reaching a peak of 0.85 percent in 1985 before declining to 0.57 percent in 1997, according to CPS tabulations (Handel 2000, p. 176).

1995. The picture is clouded further by the fact that many with undergraduate degrees in other fields enter IT occupations after taking selected college, community college, proprietary school, or vendor courses or acquiring IT skills through self-study or work experience. In the mid-1990s, slightly more than 9,000 associate's degrees were awarded in IT-related fields per year, although this figure does not include those who completed nondegree courses and shorter certificate programs. Although some believe that vocationally oriented programs may be more flexible in responding to current and fast-changing industry needs than 4-year universities, there is also concern that such knowledge is relatively narrow and may not involve the deeper conceptual understanding required to meet higher level needs or adapt to future changes (U.S. Department of Commerce 1997, pp. 33 ff.; Veneri 1998; Freeman and Aspray 1999, pp. 78 f., 99 ff.; U.S. Department of Commerce 1999, pp. 40, 77, 80 f.; and National Research Council 2001, pp. 230 ff., 247). About one-third of IT professionals (computer scientists, computer engineers, systems analysts, and programmers) do not hold a 4-year college degree, although the majority of these have had some college education (U.S. Department of Commerce 1999, pp. 24, 33). A followup report suggested ways to increase college enrollment in IT fields, including improving the image of technical professions; providing better information about career opportunities to students, parents, and teachers; and strengthening elementary and secondary math and science education (U.S. Department of Commerce 1999, p. 55).

The followup Department of Commerce report anticipated that demand would remain high. According to projections from the Department of Labor's Bureau of Labor Statistics, the number of IT professionals will grow from 1.5 million in 1996 to 2.6 million in 2006, requiring more than 1.3 million new IT professionals to fill the new jobs and replace those vacating positions, about 138,000 new workers per year (U.S. Department of Commerce 1999, p. 25).

One proposal that employers advocated to meet their needs was lifting the cap on the number of H–1B visas granted to foreign high-technology professionals, which allowed them to work in the United States for up to 6 years. Before 1998, the number of H–1B visas was capped at 65,000, half of which had been issued to those in IT fields by 1997. Employee groups opposed raising the cap, arguing that sufficient qualified Americans were available to fill any vacancies, but the industry sought to control labor costs by hiring cheaper foreign workers. Employee groups also argued that raising the cap would reduce the incentive for employers to retrain higher paid older workers and actively recruit women and minorities as well as discourage young Americans from entering the field, reinforcing dependence on foreign labor. Compromise legislation at the end of 1998 increased the cap on H–1B visas to 115,000 for 1999 and 2000 but returned it to 65,000 by 2002 and required employers using the program to contribute to a scholarship fund for low-income students and attest that they have not laid off or bypassed available American workers to hire H–1B visa holders (U.S. Department of Commerce 1999, pp. 16 ff.).

In part, the perceived shortage reflects the fast-changing and quite specific nature of high-level IT skills and the intense competitive pressures that lead companies to feel a sense of urgency to meet this niche demand. It also prompts companies, particularly smaller firms, to seek workers who already have the necessary skills rather than retrain more generally skilled IT workers, resulting in high levels of poaching of other firms' employees and job-hopping among highly skilled IT workers. This churning is not all bad insofar as workers learn by doing; repeatedly moving to more cutting-edge workplaces exposes workers to more recent technologies, which can enhance skills and avoid rapid skill obsolescence (U.S. Department of Commerce 1999, pp. 1, 9 ff., 86 f.). However, the reluctance to retrain can lead firms to simultaneously lay off one type of worker and search for another, contributing to perceptions of shortage. The rapid pace of skill obsolescence and the need for continual retraining make this a potentially chronic issue (Freeman and Aspray 1999, pp. 47, 72).

However, many analysts question whether a shortage of IT professionals ever really existed. One report argued that the lack of reliable data on the supply of and demand for IT workers prevented any meaningful quantitative assessment of a national shortage of IT workers (Freeman and Aspray 1999, p. 56). Trade association data are generally less reliable than government data (Freeman and Aspray 1999, p. 124). The General Accounting Office (GAO) criticized the original ITAA study for the low response rate to its survey (14 percent) and small sample size ($n = 271$). For all the concern ITAA's report generated, the quality of the evidence was remarkably thin. However, a subsequent ITAA study, which seemed to be more sound and had a higher response rate, found 346,000 unfilled jobs, an even greater number than the previous study (U.S. GAO 1998a; and Levy Economics Institute 1998, p. 5).

Others point to the fallibility of previous forecasts of future demand for other occupations, such as a predicted imminent shortfall of scientists and engineers in the late 1980s that failed to materialize, among others (Levy Economics Institute 1998, p. 8; and Freeman and Aspray 1999, pp. 46, 61).

Analyses using more reliable government data call into question the severity of any shortage of IT professionals. CPS data show nominal wage growth for IT professionals between 1983 and 1998 that is close to that for all occupations and slower than that for lawyers and doctors, although the boom years from 1995 to 1998 show some change. In the late 1990s, perhaps out of concern over the year 2000 problem, the wages of computer systems analysts and scientists significantly outpaced those of other professionals, although not the workforce as a whole, and computer programmers saw their wages grow significantly faster than all workers and other professionals. However, in real terms the wages of IT professionals did not grow significantly between 1989 and 1997. Private salary surveys in the late 1990s, which often included bonuses and stock options, showed greater growth for IT professionals, although the reliability of these surveys is often questioned. CPS data indicate that the unemployment rate for IT professionals was about 0.5 percentage points below that for all professionals between 1993 and 1998, falling to about 1.5 percent by 1998. This rate suggests a labor market that is tight, but not dramatically tighter than that for all professionals, who were not perceived as in critically short supply (U.S. GAO 1998b; Levy Economics Institute 1998, p. 5; Veneri 1998; Freeman and Aspray 1999, p. 57; and U.S. Department of Commerce

1999, pp. 41 f., 48). Some economists conclude from these data that the tight labor market for IT professionals in the late 1990s is mostly another example of the tight labor market for all professionals at that time (Lerman 1998).

A comprehensive review of the issue by the National Research Council (2001) of the National Academy of Sciences largely replicates previous results regarding wages and unemployment rates. The report cautions that the absence of data with more specific occupational codes might well obscure shortages for specific skills and occupations and the lack of information on stock options and other nonwage compensation might obscure broader increases in total compensation. Most notably, the report concluded that the existence of H–1B visas probably exerts some downward pressure on wages of domestic IT professionals of unknown magnitude, but more intensive use of retrained older, native IT professionals would not be sufficient to satisfy demand. The evidence for age discrimination is mixed and inconclusive (National Research Council 2001, pp. 142 ff., 175 ff.).

Chapter 7: The Debate Over Skill-Biased Technological Change and Earnings Inequality

Introduction

The main debate over the effects of IT on the labor market is much more general than the issue of IT professionals and originates with controversies outside IT.

In the 1980s, Harrison and Bluestone (1988) argued that earnings inequality in the United States had grown rapidly because of institutional changes such as:

- sectoral employment shifts from manufacturing to low-wage services,
- declining unionization rates,
- the declining real value of the minimum wage,
- greater use of part-time and temporary workers,
- increased outsourcing by large firms to low-wage suppliers,
- the transfer of domestic production to lower wage regions in the United States and abroad,
- increased import competition from low-wage regions such as East Asia and Mexico,
- deregulated product markets in industries such as air travel, telecommunications, and trucking, and
- a philosophical shift on the part of employers following the deep recession of the early 1980s to contain or reduce wage costs as a method of maintaining competitiveness (Bluestone and Harrison 1982, 1988; Harrison 1994).

Although the conclusions regarding earnings inequality and industrial sectoral shifts were drawn from analyses of the CPS and published government data, most of the causal explanations were inferred from more impressionistic evidence.

Harrison and Bluestone's thesis engendered controversies that continue to the present. Critics in the 1980s took issue with the basic thesis of inequality growth, arguing either that there was no genuine growth in earnings inequality or that any such growth was temporary, reflecting the recession of the early 1980s, the temporarily high value of the dollar that depressed U.S. manufacturing sales, or the recent entry of large numbers of lower paid younger workers and women into the labor market. These problems would work themselves out in time with an upturn in the business cycle, more realistic exchange rates, and the accumulation of experience by workers just beginning their careers. Most of these analyses also used the CPS to analyze basic trends in earnings inequality, so some of the disagreements with Harrison and Bluestone reflected different interpretations of the same data, but some of the causal inferences drawn in these accounts were likewise based on more informal methods (Lawrence 1983, 1984; Rosenthal 1985; McMahon and Tschetter 1986; Lerman and Salzman 1988; Kosters and Ross 1987, 1988; and Levy 1987; for a summary of this early debate, see Loveman and Tilly 1988).

By the end of the 1980s, more rigorous research using the CPS confirmed to the satisfaction of a wide spectrum of economists that the growth in earnings inequality in the 1980s was genuine, not a measurement artifact, and had outlasted the upturn in the business cycle, fall in the dollar's value, and career earnings growth of baby boomers and recent female entrants into the labor market. This work demonstrated that earnings inequality rose strongly in the 1980s to the highest level in the postwar period. These studies also showed that after declining in the 1970s, the education differential grew dramatically in the 1980s while the gender gap narrowed. In addition, *residual inequality* grew dramatically, that is, the dispersion of wages grew even after statistically controlling for the effects of variables such as education, experience, and gender. Because residual inequality is by definition that portion of the overall inequality of wages that cannot be explained by measured variables, explanations for the growth of residual inequality are necessarily speculative in the absence of additional control variables (Bound and Johnson 1992; Juhn, Murphy, and Pierce 1992; Katz and Murphy 1992; Levy and Murnane 1992; Murphy and Welch 1992; Danziger and Gottschalk 1995; and Gottschalk 1997). Cross-national research using comparable government and other national data sets suggested similar trends in some, although not all, other industrialized nations (Gottschalk and Smeeding 1997).

Although they confirmed the significance of the trend toward greater labor market inequality, none of these studies endorsed Harrison and Bluestone's (1988) explanations for the shift. They noted that the education wage premium grew even as the relative supply of well-educated workers grew, implying a rising demand for more-skilled workers. The cause of this rise in demand was attributed to IT, which was such a visible addition in many workplaces. This thrust IT into the center of the debate over the growth of earnings inequality, although initial explanations focusing on IT were based simply on inference and had little specific evidence to support them.

Some early studies noted that the apparent skills shortage could be due to either an acceleration in SBTC or a constant rate of technological change combined with a reduced growth of educated labor, caused by smaller cohorts of younger workers and relatively stagnant college attendance rates (Katz and Murphy 1992, pp. 50, 69; and Murphy and Welch 1993). Less attention has been paid in the literature to adjudicating this issue, although SBTC is generally acknowledged as a long-term trend that predates the 1980s. Therefore, any such explanation for the dramatic growth in earnings inequality during the 1980s and 1990s must show that a new development related to SBTC, either an acceleration of the demand shift or deceleration of supply growth, also occurred during that time.

The difference between the explanations is significant for interpreting the literature reviewed here. The *demand-acceleration* version of the SBTC thesis emphasizes the revolutionary implications of IT and corresponds more to popular belief regarding IT's impact. By contrast, the *supply-deceleration* version suggests that the skill-upgrading effects of IT are similar in magnitude to previous periods of technological change but coincide with trends in demography and college attendance rates that severely constrict the growth of the supply of skilled labor. The former explanation leads one to expect that IT has dramatic skill implications, whereas the latter implies more modest effects and directs more attention to factors unrelated to technology—such as trends in demography, immigration, and educational attainment—that modulate the supply of skills rather than the demand for them. In general, most economists have implicitly given greater weight to IT as a driver of growth in earnings inequality.

The claim that SBTC explains growing earnings inequality prompted other researchers more sympathetic to Harrison and Bluestone's (1988) explanations to conduct additional research using the CPS or other government data. Most of their empirical findings are not much disputed by the researchers cited above, although the implications for explaining earnings inequality are still debated. These studies note that roughly half of the growth in earnings inequality represents growth in residual inequality and cannot be explained based on observable skill measures (Mishel and Bernstein 1998, p. 310). Most inequality growth between 1979 and 1997 occurred in the early 1980s, quite early in the IT diffusion process, and inequality remained fairly stable in the 1990s when so many advances in IT attracted attention (Howell 1995, 1997; and Handel 2000). Few measures of productivity show faster growth during the 1980s compared to earlier decades, leading to questions as to why one would expect IT to have a dramatic effect on wages during this time (Mishel, Bernstein, and Schmitt 1997). Others have found that declines in the minimum wage and declining unionization rates (DiNardo, Fortin, and Lemieux 1996) and, to a lesser extent, deregulation in some industries (Fortin and Lemieux 1997) have affected the growth of earnings inequality, but these issues are outside the scope of the present review.

The research on SBTC proceeded in a number of directions. The first research to examine the links among computers, wages, and skills directly was Krueger's (1993) study of the large wage premium associated with computer use, which he interpreted as a return to knowledge of computer software specifically. The study generated such controversy that advocates of SBTC then advanced other arguments and models. They claimed that the more significant effect of computers was that they increased the general human capital requirements of either computer users or both users and nonusers who worked in highly computerized environments because of the greater information processing, reasoning, and decision-making abilities now required. Although these explanations posited within-occupation changes in job skill content, a separate line of research examined whether IT altered the occupational distribution of workers. The research relating to these different variants of the SBTC thesis—computer-specific human capital, general human capital among computer users, general human capital among users and nonusers, and differential job creation and displacement—are reviewed in the following sections.

The Debate Over the Computer Wage Premium

Before discussing the debate over SBTC further, examining some of the trends in computer use over time may be useful. Table 5 presents tabulations from various supplements to the CPS on the percentage of all workers using a computer at work and the specific tasks for which they use a computer, as well as the annual growth rates between surveys. Direct use of computers grew rapidly between 1984 and 1993, rising from about 25 percent to about 47 percent of all workers, then rose much more slowly to about 50 percent of all workers in 1997. Word processing has always been the most widely used single application, followed by spreadsheets, bookkeeping, inventory, and databases until 1997, when e-mail became the second most widely used application.

Table 5. Trends in the Percentage Share and Annual Growth Rate of Workers Using Computers at Work for Any Task and for Specific Tasks: 1984–97

	Percentage				Annual Growth Rate		
	1984	1989	1993	1997	1984–89	1989–93	1993–97
Use Computer at Work	25.49	37.92	47.06	50.47	2.49	2.29	0.85
Specific Tasks							
Word Processing		15.14	20.46	28.28		1.33	1.96
Spreadsheet		8.43	10.81	15.99		0.60	1.30
Database		10.33	16.16	16.83		1.46	0.17
E-mail		5.83	10.38	23.66		1.14	3.32
Internet use		n.a.	n.a.	16.29		n.a.	n.a.
Bookkeeping		9.23	11.10	13.92		0.47	0.71
CAD		3.41	3.44	n.a.		0.01	n.a.
Programming		7.20	6.11	7.49		–0.27	0.35
Inventory		9.58	11.73	14.28		0.54	0.64
Invoice		6.19	8.68	11.10		0.62	0.61
Sales		5.57	6.47	10.27		0.23	0.95

Source: U.S. Census Bureau, Current Population Survey, October Supplements 1984–97. Author's calculations from Handel (2000). All figures weighted. Specific computer task items not asked in 1984. Internet use not asked in 1989 and 1993. CAD use not asked in 1997.

Additional tabulations not shown here reveal other interesting patterns. White collar workers, particularly clerical workers, those with more education, women, and whites are significantly more likely to use computers than others. Perhaps contrary to stereotype, workers between the ages of 25 and 54 use computers at roughly similar rates and are significantly more likely to use computers than workers who are either younger or older (Krueger 1993, p. 36; and Handel 2000, p. 282). The rise in computer use and its uneven distribution among different segments of the workforce represent potentially significant developments.

However, initial claims that IT produced a skill shortage that raised inequality by driving up the relative wages of more-skilled workers were based on the observation that the relative wages of more-educated workers grew in the 1980s at the same time that the relative number of such workers also grew, implying some type of demand shift in favor of more-skilled workers according to traditional neoclassical economic theory. The task, then, was to find direct evidence of a link between IT and wages or skills that would give this *prima facie* case specific support.

The first study to do so was Krueger's (1993), which pioneered the use of CPS supplements with individual-level data on computer use as well as traditional labor market information. Krueger found that computer use among wage and salary workers rose from about 25 percent in 1984 to about 37 percent in 1989. More important, he found that when computer use at work was added to a standard wage regression, computer users appeared to earn about 15 percent more than nonusers, controlling for education, experience, race, gender, marital status, hours worked per week, union status, broad occupational group, and region. When two-digit industry dummies were included, the coefficients were closer to a 10 percent differential. The inclusion of the computer use variable also explained about 40 percent of the 0.01 growth of the education premium between 1984 and 1989. This is a within-occupation account of skill upgrading in that it finds that computers have an effect on wages after controlling for other aspects of jobs; this study claims to isolate the effects of the introduction of computers on a job's skill requirements rather than, for example, on changes in occupational composition as a result of more extensive automation of less-skilled occupations.

Krueger (1993) performed a number of checks to test the validity of his results, such as testing whether computer use was associated with more prosperous employers or preexisting worker quality differences that were also associated with higher wages. Although others would argue that economic theory would not predict an observed premium because nonusers with (unobserved) computer skills would have to be compensated for their human capital just as otherwise similar users were, results indicated that home computer users did not receive a wage premium comparable to users at work (Krueger 1993, pp. 43 f.). From this and other sensitivity tests, Krueger concluded that these preexisting differences did not account for the wage differential between computer users and nonusers. This study seemed to provide strong evidence that "employees who use computers at work receive a higher wage rate as a result of their computer skills" and that the diffusion of computers in the workplace "has significantly contributed to recent changes in the wage structure," particularly through its effects on raising the rewards for education or skill (Krueger 1993, pp. 37, 55). Krueger proposed expansion of computer training as a relatively simple way to reduce inequality.

The study generated a great deal of attention for its apparently clear demonstration of a link between computer use and rising earnings inequality using nationally representative data, but the initial impression did not last. DiNardo and Pischke (1996, 1997) analyzed three nationally representative German government surveys from the late 1970s to early 1990s and showed that using calculators, telephones, and pens or pencils at work—or even sitting down while working—were associated with premiums comparable in size to those for computer use when each was entered individually in a standard wage equation. They argued that the actual productivity differential associated with each characteristic was unlikely to produce such similar results. Likewise, the large coefficients for working with pens and pencils and sitting at work suggested that these variables do not primarily measure scarce, productivity-enhancing skills, such as the ability to use pencils, sit down, or even use a computer, but some unobserved aspect of either human capital or occupational position, for which the different measured variables served as proxies. The effects associated with computer use remained among the largest when all job characteristics were entered together into a wage equation, but DiNardo and Pischke argue that each variable is an imperfect proxy for worker ability or type of job, with some picking up this variation better than others. They suggested that the relationship between computer use and wages is indeed spurious and reflects unobserved heterogeneity in either human capital or occupational position. DiNardo and Pischke suggested that technology per se may explain little of the growth in earnings inequality in the 1980s.

Even many who supported an SBTC explanation of rising earnings inequality found this work effectively debunked the conclusions of the previous research, and attention turned toward other ways of specifying a connection between IT and wages or skill demands. However, Krueger's (1993) study generated a great deal of further research worth reviewing for a number of reasons.

First, the notion that computers or other high-technology equipment requires significant skill to operate, which may have increased the wages of those more skilled, is among the most straightforward and intuitive accounts of a possible link between IT and inequality growth. Indeed, some recent papers continue to cite Krueger's (1993) study as support for the SBTC thesis and use similar regression specifications (Black and Lynch 2000, p. 15 and tables 3 and 4; Cappelli and Carter 2000; and Friedberg 2001, pp. 4 f.), and Krueger himself still argues for the original thesis, although less strongly, and he acknowledges the importance of DiNardo and Pischke's (1996, 1997) findings (Krueger 2000, pp. 15 f.).

Second, the wealth of subsequent research on this topic is hard to ignore. Krueger's (1993) original study and DiNardo and Pischke's (1996, 1997) response stimulated numerous additional studies that are useful to summarize given the interest this topic generated.

Third, models that purge coefficient bias by accounting for person or employer fixed effects would also speak to other SBTC theories that distance themselves from the computer wage premium literature Krueger (1993) initiated, which posit that increases in general human capital demands among computer users rather than computer-specific skills are the source of SBTC. Because some studies of the computer wage premium do incorporate person and employer fixed effects, they speak to the issue of whether computer use is associated with skill upgrading regardless of the source.

Whereas DiNardo and Pischke used data from Germany, which did not experience rising wage inequality in the 1980s, Handel (2000) replicated their central findings for the United States using a 1991 supplement to the CPS. Results indicated that various noncomputer job tasks, such as writing memos and reports at work or reading and using letters, forms, and diagrams, were associated with wage differentials roughly comparable to the computer premium when entered individually into a standard human capital wage model, although the computer coefficient remained the strongest when all were entered jointly in a single model. Nevertheless, just as one would not conclude that there is a wage payoff to letter-reading skills specifically rather than to the occupational status or general abilities for which they presumably proxy, the computer coefficient should not necessarily be considered an unbiased measure of returns to this specific skill. In addition, workers who reported that their computer skills were not good enough for their current job did not suffer a wage penalty, nor was experience with computer training associated with a wage premium, at least in the cross-section.

Handel (2000) noted further difficulties with the original computer study, including that, among specific computer applications, using e-mail received the largest additional wage differential beyond the baseline computer premium, whereas programming and computer-aided design brought no additional reward; this is hard to reconcile with the notion that the different coefficients reflect returns to the respective human capital requirements of these tasks. In addition, the growth of earnings inequality between 1979 and 1993 was concentrated in the early 1980s, and nearly half of that growth occurred during the high unemployment period 1981–83, whereas inequality changed little in the 1990s; this timing seems more related to macroeconomic conditions than to the diffusion of IT. In addition, comparing measures of inequality for 1984 and 1989 after statistically adjusting computer use in the 1989 CPS sample to 1984 levels accounted for little of the growth of earnings inequality in that period (Handel 2000).

The literature discussing the computer wage premium assumes that computer skills are scarce and expensive. The prevailing assumption seems to be that workers must adjust to technology as though it were an external force. However, this assumption represents only part of the picture because it is in the nature of computer product markets that the technology must adjust to users. However complex they may be internally, equipment and software that are hard to use are at a competitive disadvantage. If word processing software required users to have skills comparable to programming in FORTRAN or C, there would be far fewer word processors. The competitive advantage of usability drove the development of the graphical user interface, whose icons and pull-down menus replaced arcane commands with pictures. There are some complexities to the process, notably the tendency for software to become feature-rich, hence more complex, even as core functions are simplified. Still, one should not assume that high technology necessarily demands high skill requirements. Inevitably, there is some kind of mutual adjustment between vendors and users (Handel 2000).

As with DiNardo and Pischke (1997), a study using the Canadian General Social Survey (1994) found a computer premium similar to that found by Krueger (1993), but the study also revealed that use of a fax machine was associated with a larger and more robust wage differential than use of a computer. Because it is unlikely that the use of fax machines had such a strong effect on skill requirements, the authors also question whether the computer use premium can be taken at face value (Morissette and Drolet 1998).

Research using the British National Child Development Study of those who were 33 years old in 1991 found that the use of tools at work normally associated with manual labor is not a robust predictor of wages in a standard wage regression that also includes occupation, industry, firm size, and math and reading test scores, whereas the computer premium remains significant ($\beta = 0.07$, $t = 4.01$). A variable measuring whether individuals have gotten "better in using a computer to solve problems or give information" in the past 10 years is also associated with a wage premium in the same model ($\beta = 0.031$, $t = 1.91$), leading the authors to argue with Krueger that the results reflect rewards for computer skills specifically. The percentage of the working day employees spend at a computer is also associated with higher wages ($\beta = 0.058$, $t = 2.89$) (Arabsheibani and Marin 2000, p. 14).

Another British study using a nationally representative sample, the Skills Survey of the Employed British Workforce (1997), found that four levels of complexity of computer use—simple, moderate, complex, and advanced (Green 1998, pp. 10 f.)—are generally associated with successively higher wage premiums, with the lowest level receiving a 4–7 percent differential depending on gender and the most advanced receiving a 15–20 percent differential after controlling for other specific job skill requirements, establishment size, and standard human capital variables. The author acknowledged, however, that these results do not settle the question of whether computer use causes higher pay or is associated with other unobserved variables that affect pay (Green 1998, p. 14).

Indeed, frequency of computer use at work is associated with successively higher wage premiums in the CPS (1991) for the United States, but the same relationship is found for other job task measures with implausibly high premiums, such as reading letters at work. This finding may merely indicate that some unobserved characteristics that are associated with higher wages are also associated with more frequent or complex use of computers (Handel 2000).

By contrast, a Dutch study used panel data on a cohort that was age 53 in 1993 and found that the size of the computer wage premium was not consistently greater for those who use computers at work more often when added to a standard wage equation that also includes an IQ measure. This study also found that wage growth between 1983 and 1993 was not consistently associated with intensity of computer use in 1993 (Oosterbeek 1997).

A British study using repeated cross-sections for 1986, 1992, and 1997 found that job skill demands, as measured by employee reports of the level of education, training, and on-the-job experience required for their jobs, rose during this period. Computer use is strongly associated with these indicators in a model that pools all years and controls for only establishment size and industry; previously significant year dummies become insignificant when computer use is added to the model (Green, Felstead, and Gallie 2000). However, the sparse use of control variables, including the absence of occupational controls, makes these results difficult to accept at face value.

Because of the concern over the possible spuriousness of measured returns to computer use, other studies have attempted to more effectively control for possible confounding variables.

Black and Lynch (2000) used panel data from two waves of the National Employer Survey (NES) (1993, 1996) to estimate fixed-effects models for employing establishments that control for unobserved time-invariant establishment characteristics. The survey excluded establishments with fewer than 20 employees, and the study restricted analysis to the roughly 250 manufacturing establishments with data on all variables for both years, but it was otherwise representative. Black and Lynch found that the proportion of nonmanagers using a computer is associated with a 15 percent wage premium for production workers in the 1996 cross-section, but the effect disappears entirely in the fixed-effects model that uses changes in the percentage of workers using a computer to predict changes in average wages within establishments (Black and Lynch 2000, tables 3 and 4).

Results in Cappelli and Carter (2000) are more favorable to the computer premium thesis. They found that first difference models using the NES panel data yielded few significant effects for various predictors, and they inferred that the method exacerbates measurement error from both survey waves. They pooled the data for both years for all industries and found that the percentage of nonsupervisory workers using computers is significantly associated with production worker wages but that the percentage of managerial and supervisory workers using computers shows almost as strong a relationship with production worker wages. The same pattern is found for a number of other occupations, and the proportion of computer users among production workers actually has a stronger effect on the pay of managers and professionals than computer use in their own occupation (Cappelli and Carter 2000, pp. 19, 21). However, given the large number of establishment-level controls, they concluded that "the higher wages [among computer users] are not simply an artifact of unobserved firm characteristics" (Cappelli and Carter 2000, p. 23).

Hamilton (1997) argued that because those with computer skills are not drawn randomly from the wider population but may have some additional unobserved characteristics associated with higher wages, researchers cannot generalize observed computer wage premiums without controlling for possible selection effects. The High School and Beyond Survey (1986) has data on computer skills, such as whether respondents ever used word processing, spreadsheet, and other common software applications as well as whether they had written programs in FORTRAN, COBOL, or other advanced computer languages. The sample was restricted to males graduating from high school in 1980 who worked more than 20 hours per week.

A standard wage regression finds a computer premium roughly in the 5–10 percent range among whites and almost double that among blacks. Including math and verbal test scores does not significantly affect the size of the computer skill premium when added to a standard wage regression. To control for possible selection effects, Hamilton also estimates the model after including predicted values from a selection equation that estimates the probability of acquiring computer skills using variables for whether the respondent thought math was interesting or useful when surveyed in high school and whether his family owned a pocket calculator when he was growing up as well as the predictors from the wage regression. In these models, hourly wages were 25 percent higher for workers with computer skills when measured as knowledge of word processing and other common applications and 13 percent higher when skills were measured by high-level programming knowledge, although the gap is slight for college graduates (Hamilton 1997, table 5). As with Krueger's earlier results, it is not clear why knowledge of programming fails to confer substantially greater advantages than knowledge of common applications if the wage premium reflects relative levels of human capital.

Friedberg (2001) used instrumental variables to test whether the human capital requirements for learning how to use computers were sufficiently great that some older workers retired earlier than they would otherwise rather than undertake the necessary training. She noted that the narrow variation in computer use rates for those ages 25–53 suggests that people acquire computer skills as needed for their jobs, regardless of whether they had prior experience with computers, for example, in school (Friedberg 2001, pp. 7 f., 20). This finding suggests that early retirees may have chosen to forgo computer training because they had already decided to retire, not because acquiring the necessary skills was too difficult.

However, Friedberg (2001, p. 13) believed that the decision not to undertake computer training causes some workers relatively close to retirement to retire earlier than they otherwise would have. Results from an initial ordinary least squares model indicate that workers ages 50–62 in 1992 who used a computer at work were 2.2 percentage points less likely to retire 4 years later, but this does not disentangle the two types of causal effects. When average computer use among prime-age workers in the same occupation and industry is entered as an instrument to simulate the exogenous introduction of computers, Friedberg found that using a computer at work makes someone 6.6 percentage points less likely to retire and delays retirement by about 8–12 months (Friedberg 2001, pp. 17 f.). Friedberg's results seem a bit paradoxical: She acknowledged that the lack of an age gradient in computer use for prime-age workers suggests that computer skills are easily acquired, yet she also tried to show that they require sufficient human capital investment as to be a meaningful source of early retirement. Other data and case study reports also suggest that older workers have a harder time adjusting to the arrival of computers, but the number of early retirements seems small and is presumably a transitory problem given the increasing diffusion of computers (Zuboff 1988, p. 74).

One of the most unusual studies used a sample of roughly 600 identical twins and found that the strong effects of computers on wages in a standard regression model disappears once the effect is estimated from the variation in computer use within twin pairs, which controls for common family background and ability variables. The author concluded that "computers in the workplace do not themselves create a wage premium for a given worker; instead, the results indicate that more able workers tend to work at jobs which require the use of a computer" (Krashinsky 2000, p. 11).

Use of employee-level panel data, such as Oosterbeek's (1997) study, described above, is generally considered the best way to control for stable individual characteristics. There are individual studies for the United States, United Kingdom, France, and Germany.

Johnson (2002) analyzes wage growth for a three-wave panel of former welfare recipients in an urban Michigan county for 1997–99. In cross-sectional analyses, computer users earn 8 percent more than nonusers when they start using a computer and an additional 3 percent with each additional year of experience using a computer. However, in a first-difference model, both coefficients are insignificant, suggesting that it is not computer use or skill per se that is rewarded but other, unobserved worker characteristics that are associated with computer use. By contrast, other variables, such as reading and writing use on the job and keeping close watch on gauges, dials, and instruments, are associated with even greater rewards in the first-difference model relative to the cross-sectional analyses (Johnson 2002, pp. 20 ff.)

Bell (1996) used wage data from the 1981 and 1991 waves of the British National Child Development Study and information about computer use at work from the 1991 wave for those who were 33 years old in 1991. Cross-sectional estimates indicated a computer premium of about 12 percent after controlling for math and reading test scores, industry, occupation, establishment size, supervisory responsibilities, and standard human capital variables, among others (Bell 1996, table 5). As with the original computer premium study, reported computer abilities are not rewarded if the individual does not actually use computers on the job (Bell 1996, table 3), contradicting the view that the search for computer wage effects among users is misguided because nonusers with computer skills will also receive the premium if they are to be attracted to noncomputer jobs. Computer users in 1991 did not receive higher wages than others in 1981, when they were 23, which argues against the objection that computer use merely proxies for other, more stable individual differences (Bell 1996, table 7). Computer use explains about 40 percent of the rise in returns to educational qualifications in the United Kingdom, similar to Krueger's estimates for the United States (Bell 1996, p. 15). Finally, using a first-difference model of wage growth for those who did not change employers between 1981 and 1991 to control for unobserved individual and firm characteristics, Bell found that the computer coefficient remains significant but is reduced to about a 6 percent premium (Bell 1996, table 8).

However, rather surprisingly, the computer premium tends to be similar in magnitude to another skill variable that measures whether the respondent is involved in running an organization, group, or firm. Such involvement would seem to require a much higher level of skill, and this result is consistent with DiNardo and Pischke's (1997) warnings about the trustworthiness of the measured returns to computer use (Bell 1996, table 4).

Entorf and Kramarz (1997) analyzed panel data from the French Labor Force Survey (1985–87), which contains detailed information on technologies used in the 1987 wave and can be matched with data on firm characteristics. Most employees are using new technologies the authors classify as allowing autonomy (e.g., microcomputers), and they receive a 16 percent premium in a cross-sectional wage equation, which declines to about 4.5 percent for those with 6 years of experience with the technology when preexisting individual characteristics are controlled in fixed-effects models; inclusion of firm characteristics does not significantly alter results. Smaller numbers of workers using technology classified as not involving autonomy (e.g., robots or numerically controlled machine tools) do not receive any premium (Entorf and Kramarz 1997, pp. 1494 ff.).

Entorf, Gollac, and Kramarz (1999) updated these results using a 1993 supplement to the Labor Force Survey on new technology use. They found that cross-sectional estimates of the returns to computer use of 15–20 percent fall to 2 percent after 1–3 years of experience with computers and then to zero when longitudinal data are incorporated into models. Computer users are better paid than nonusers, but they were better paid even before they began using computers. As with the earlier survey (Entorf and Kramarz 1997), the inclusion of firm fixed effects has little effect on results (Entorf, Gollac, and Kramarz 1999, p. 476).

Again, some anomalies appear with specific estimates. The 1987 cross-sectional premium for microcomputer use ($\beta = 0.071$) is similar in size to the premium for using at work an early and primitive French version of the Internet called Minitel ($\beta = 0.069$), which did not require significant training and was distributed by the French government to any household requesting it. Using a fax machine is associated with a somewhat smaller but still significant premium ($\beta = 0.037$), whereas using a robot or numerically controlled machine is not associated with any significant wage differential, although these results may reflect the fact that only about 1 percent of the sample used each type of technology (Entorf and Kramarz 1997, pp. 1497, 1506; Entorf and Kramarz 1998, pp. 178, 192). These results are somewhat stronger in the 1993 data, with significant coefficients for computer use ($\beta = 0.0979$), fax machine use ($\beta = 0.1204$), and Minitel use ($\beta = 0.0470$), but no significant effect for robot use ($\beta = 0.0249$) (Entorf, Gollac, and Kramarz 1999, p. 475).

The German Socio-Economic Panel has information on computer use at work for 1997. Cross-sectional results using a standard human capital model indicate a 7 percent computer wage premium, but fixed-effects models estimate a computer wage premium in the range of 1–2 percent (Haisken-DeNew and Schmidt 1999).

In general, this literature is inconclusive regarding the existence of a genuine computer wage premium or the difficulty level of the new skills introduced by computers in the workplace.

Alternative Explanations and Econometric Evidence on the Links Among Computers, Skills, and Wages

The confused state of the evidence and interpretation regarding the computer wage premium led others advocating the SBTC thesis to propose different mechanisms by which computers and IT might increase the demand for and wages of skilled labor. These theories are not as easily stated as Krueger's original thesis; i.e., computers affect wages and inequality because of the specific training and knowledge needed to operate them. Many of the theories discussed in the following sections are implicit or not discussed in depth in the relevant works. One can tease out of the literature the following possible explanations for why computers increase the demand for skill, which need not be mutually exclusive.

(1) *Direct impact of computer use through computer-specific human capital (within occupations).* The equipment and software are difficult to learn (Krueger 1993).

(2) *Direct impact of computer use through general human capital (within occupations).* Equipment and software may not be complex, but computer use requires more cognitive skills, especially in jobs for less-skilled workers, because computers:

- Replace the demand for physical sensing, tacit skills, and intuition with demand for greater literacy and more abstract, formal, and procedural reasoning skills.
- Replace jobs with narrow responsibilities with jobs with broader responsibilities, which requires an understanding of the interrelationships among integrated production systems, greater general cognitive or conceptual skills, intellectual flexibility, and systems thinking.
- Encourage employers to delegate to less-skilled workers conventional tasks that previously were bundled into more-skilled jobs, such as elementary bookkeeping for secretaries or inventory recordkeeping for forklift operators.
- Encourage employers to structure work more thoroughly in ways that give front-line workers training in and responsibility for broader and more varied job tasks, quality control, problem-solving, and decision-making as part of new participative management techniques, often called *high-performance work practices* (Hirschhorn 1984; Zuboff 1988; Bresnahan, Brynjolfsson, and Hitt 1999, 2002; Siegel 1999; pp. 19 f.; and Fernandez 2001).

(3) *Indirect impact of computerization through general human capital (within occupations).* Computers may require more general cognitive skills because they increase the overall quantity, variety, and complexity of information for all types of jobs in ways

unrelated to the operation of computers themselves. A computerized work environment may raise the skill demands of tasks performed by computer users and nonusers alike (Autor, Katz, and Krueger 1998; Autor, Levy, and Murnane 2000).

(4) *Indirect impact of computerization through job creation and displacement (between occupations).* IT may alter the demand for skills through changes in the occupational distribution by either:

- Creating more jobs at the top and in the middle of the skill hierarchy—not simply technicians and IT professionals who install, maintain, and manage the systems themselves, but also non-IT professionals who analyze and act on the information generated by the systems (e.g., accountants and production planners); or
- Destroying jobs at the bottom through automation (e.g., factory robots replacing assembly line workers or optical character recognition technology replacing data entry workers) (Berman, Bound, and Griliches 1994; and Danziger and Gottschalk 1995, p. 141).

The first explanation is the one implied most strongly by the computer wage premium literature discussed previously. The second specifies alternative mechanisms; however, because they imply skill effects for computer users specifically, any test would presumably involve the same types of models and issues found in Krueger (1993) and those responding to his work. In other words, they imply different interpretations of the computer wage premium but a computer wage premium nonetheless; they offer an alternative interpretation of computer wage models and their coefficients but not an alternative underlying model or specification. The third explanation is much more distinct but also more difficult to test because it posits a contextual effect and the causal mechanisms are harder to specify. This model implies action at a distance; a computerized environment affects job demands regardless of whether one uses a computer and the level of one's involvement with computers. Direct computer use at work is incidental to the model. The introduction of computers in a firm seems to put more information and job complexity in the air, as it were, affecting diffusely all kinds of jobs although, as will be shown, some try to pin down the source of such effects more specifically. The fourth explanation is different from the others because it specifies various between-occupation skill shifts rather than within-occupation shifts.

Although not every study can be assigned neatly to a single framework of explanation, the discussion below is organized according to these categories. Because the previous section covered the first class of explanations, which might be called the direct impact of computers through computer-specific human capital, this discussion covers the remaining class of explanations.

Direct Impact of Computer Use on Skills and Wages Through General Human Capital

Although knowing how to operate a computer in a narrow sense may not in itself require great additional skill, certain dimensions or correlates of using IT may demand significantly greater cognitive skills, initiative, and responsibility. In this view, it is not computer-specific training per se that introduces significant new skill demands but the increased general intellectual or human capital requirements that often accompany computer-based work.

Drawing conclusions from eight case studies conducted in diverse work settings in the early 1980s, Shoshana Zuboff (1988) argued that blue and white collar workers using precomputer technologies learned by doing, and their knowledge was often tacit, intuitive, experience-based, and concrete, in the sense that it was hard to state explicitly, known in "one's bones," and context-bound. By contrast, she argued that work with computers and other IT requires knowledge that is explicit, formal, abstract, conceptual, and often learned through formal instruction, seminars, or classes. In Zuboff's view, computers involve the manipulation of symbols rather than physical objects, and this requires a new way of thinking at work.

These case studies suggested that factory work increasingly involves programming, monitoring, and remotely controlling stand-alone machines and integrated processes, often in separate rooms with little direct sensory contact with the physical process. Back-office work no longer involves processing paper records but working with computer databases organized according to an intangible, abstract structure and governed by abstract codes and commands. Information is recorded more quickly and can automatically trigger other operations (e.g., mailing a check) that can be hard to reverse. Workers are under increased pressure for accuracy and greater demand for concentration and attention to detail. Even managerial and professional tasks, such as judging creditworthiness for a loan, which formerly involved intuition and interpersonal skills, now rely more on impersonal data and computer models. Many more managers use computers to review operational details, access and analyze data, and generate reports. IT also permits firms to expand the scope of their products and customize goods and services, and this increased novelty can also create a demand for more intellectually flexible labor.

In this view, work in the computer era involves more information management among all types of workers. Workers face new demands for memory, attention and concentration, procedural reasoning, foresight, formal knowledge, conceptual maps, and systems understanding of underlying processes and interrelationships. As one government report claimed, "higher level problem-solving skills have almost certainly increased in value with the availability of computers" (Executive Office of the President 1996, p. 202).

In addition, because all workers now have at their fingertips information that previously was difficult to assemble and restricted to managers, they can now track output and quality statistics and conduct their own investigations to improve processes or add value. The flexibility of computers allows for rapid adjustment to changing market conditions, but only if those close to operations are given the skills to perform functions previously divided into separate jobs and the authority needed to make quick changes. Firms with hierarchical cultures may still refuse to allow workers free access to or use of data, but the cost of excluding workers from decision-making roles rises with the availability of computers (Zuboff 1988). Thus, firms are experiencing pressure to restructure the workplace to delegate more responsibility and initiative to lower level employees, sometimes known as "empowerment" or “high-performance work practices.”

However, Zuboff (1988) acknowledged that many of these developments are matters of managerial discretion. Computers can lower substantive knowledge demands when rules, procedures, and calculations are programmed into the computer system in place of reliance on the worker and no significant new skills or role requirements are added to a job. Managers can sometimes guard their privileges rather than move to a more participative system. In this case, workers become adjuncts to the computer system, minding the equipment or performing repetitive data entry. For Zuboff, although computer technology makes a high-performance work philosophy more rational, managers who fear loss of power and control may limit the potential skill-upgrading impacts when they implement new systems. In Zuboff's view, nothing is inevitable about the relationship between computers and meaningful skill upgrading. Technology and work co-evolve with other social and institutional factors that affect the specific direction change will take.

Recently, a number of studies have adopted Zuboff's (1988) more optimistic predictions and tried to test them in the context of the debate over SBTC and earnings inequality. Because these studies do not use the four-point framework of SBTC described above, many include information on the difficulty of learning computer systems in the narrow sense, the role of computers in increasing the information content of noncomputer jobs, and the effects of computers and automation on patterns of job creation and destruction (i.e., between-occupation shifts).

Bresnahan, Brynjolfsson, and Hitt (1999, 2002) matched information on organizational structure, practices, and labor force characteristics from a cross-sectional sample of 400 large organizations covering 1995–96 with panel data on computer capital in these organizations for 1987–94. They found that different measures of IT, human capital, and high-performance work practices, such as self-managing teams, are all positively associated with one another, controlling for Standard Industrial Classification (SIC) one-digit industry and firm size. Because IT is measured before the human capital and organizational variables, they infer a causal relationship. Some associations, such as that between education level and the percentage of workers using e-mail, have a flavor similar to those that animated the discussion over Krueger's (1993) results. However, the authors interpret such variables as facilitators of more complex communication and decision-making rather than indicators of specific computer-related human capital demands (Bresnahan, Brynjolfsson, and Hitt 1999, p. 24).

Because Bresnahan and colleagues argued that IT stimulates thorough workplace reorganization, they also argue that "managerial and professional workers who never touch a computer have their work transformed" (1999, p. 17). In this sense, their work belongs in both this section and the next because it encompasses general human capital effects of direct computer use and indirect effects for both users and nonusers. The authors conclude that IT caused recent changes in organizational structure and demand for human capital and that this "technological change shows no sign of abating" (Bresnahan, Brynjolfsson, and Hitt 1999, p. 35). However, as noted above, inequality growth did abate in the 1990s, contradicting this implication of the SBTC thesis.

One of the most thorough studies in this vein, which also suggested that computers had indirect skill upgrading effects on users and nonusers as well as direct effects on users, is Fernandez's (2001) longitudinal study of a unionized food processing manufacturing plant. The company closed an antiquated plant and built a highly automated, state-of-the-art facility that became operational in 1993 while guaranteeing employment and current nominal wage levels for the nearly 200 hourly production workers from the old plant. Aside from attrition issues, this study circumvented some of the problems of unobserved ability bias in the literature stimulated by Krueger (1993) because the change in production technology is more purely exogenous.

In the new plant, operations once performed manually, such as pouring ingredients into stand-alone machines, were replaced by automated and computer-controlled materials flow and cooking processes, monitored and directed by operators in an air-conditioned control room sitting in front of computer terminals. Management explicitly gave operators more training, autonomy, discretion, decision-making authority, data interpretation responsibility, and quality control functions as part of the changeover, consistent with Zuboff's (1988) model.

Fernandez (2001) measured job skill demands in both the old and new plants with observer ratings using skill measures from the *Dictionary of Occupational Titles*; worker self-reports of education and training requirements and the use of reading, writing, and math skills on the job; and analysis of complete sets of documents workers use on the job. The evidence indicated greater job complexity in the new plant. Workers reported greater use of reading, writing, and math skills after the plant retooling of roughly 0.32 on a 5-point scale ranging from use "none at all" to "a lot" (Fernandez 2001, table 4). The average number of paper documents workers used rose from 2.6 to 10.3, not counting computer screen forms. Many paper forms are generated from computer data on output levels and quality and thus are attributable to greater IT intensity.

However, the absolute reading and math demands remained fairly simple, such as a shift from requiring only basic arithmetic in the old plant to requiring computation using decimals and ability to read a graph in the new plant. And although the increase in documents increased the amount of information workers must process, the documents' qualitative complexity, as rated using the system employed on the National Adult Literacy Survey, seems to have increased only modestly (Fernandez 2001, pp. 14, 21).

Fernandez (2001) estimated that the average training time remained constant at between 3 and 6 months under both systems, and worker self-reports also indicate no change in training times. Worker reports from the two waves indicated that the formal education workers believed their jobs required increased from 10 years to 11.5 years, still roughly equal to the average level of education of workers in the original plant. (Fernandez 2001, pp. 14 f. and table 3). Although the evidence suggests that skill demands rose, the existing workers seem to have absorbed these demands relatively easily, with no change in turnover relative to historical patterns nor any change in the racial composition (approximately 55 percent minority) despite widespread fears that minorities did not possess the skills demanded by high-technology work environments. The author acknowledged at various points that the magnitude of the within-occupation skill shifts was absorbable and did not require higher levels of formal education for production workers (Fernandez 2001, pp. 16, 25, 31, 40 f.). Indeed, Current Population Survey (CPS) data indicate that the education levels of blue collar manufacturing workers in the overall economy tended to closely track changes in the workforce as a whole (Handel 2000, pp. 164, 297).

The percentage of workers who never used a computer in their job declined dramatically from more than 83 percent to less than 10 percent after the changeover, and the percentage always using a computer on the job rose from about 5 percent to about 29 percent (Fernandez 2001, p. 22). However, the study did not address whether the skill effects of computerization were large or small, especially relative to any pressure they may have put on wages.

Fernandez (2001) noted that the increased job requirements were not associated with increased average real wages, but wage inequality within the plant increased between 1991 and 1994. Most of the growth in earnings inequality was due to the hiring of an additional three maintenance electricians at increased wages that better matched the market rate and, to a lesser extent, the hiring of an additional six maintenance mechanics; that is, small between-occupation shifts and larger changes in occupational rewards. The expensive and newly integrated production equipment raised the cost of machine downtime and increased demand for maintenance workers. These workers also made the most intensive use of computers, including separate systems for machine testing and diagnosing, e-mail for work orders, and inventory control, although again, no evidence shows how much new skill these systems introduced into maintenance jobs (Fernandez 2001, pp. 37 ff.).

Comparison of wages for less-skilled workers in the plant with average occupational wages from the Department of Labor's Bureau of Labor Statistics (BLS) Local Area Wage Survey for the region during this time indicates that they were protected from greater real wage declines in the external market either by the company's guaranteed nominal wage floor, perhaps buttressed by the institutional protections of union representation, or by the skill upgrading of their jobs, which may have made the guarantee feasible for the firm by raising the workers' value. Either way, Fernandez (2001) concluded that wage inequality would have widened further if changes in the wages of less-skilled workers had followed the direction of market wages more closely.

Despite the dramatic increase in automation, only one job was totally automated away (Fernandez 2001, p. 11). Even with the "massive upgrading" of the production technology, the plant had no difficulty maintaining employment at preautomation levels and training the existing workforce to use the new technology.

It appears, then, that automation in the new plant did not reduce employment levels but shifted the occupational composition and rewards in favor of skilled maintenance workers and upgraded the task content of less-skilled occupations to an extent that remains somewhat ambiguous.

Although the Fernandez (2001) study is among the most thorough, several barriers prevent generalizing from the results. As Fernandez argued, the firm's policies dampened any expected effects on wages and employment, suggesting that comparable cases would show greater growth in wage inequality. However, the complete substitution of a long-outdated plant with a state-of-the-art facility is also a much more dramatic change than is typical and suggests that this case should be taken as an upper-bound estimate of the effect of IT on changes in skill demands at the plant level. In addition, the relatively low frequency of this type of total change at any point in time limits its explanatory power of inequality growth at the aggregate level. In other words, this study likely measures the greatest skill effects one might expect from IT in manufacturing that are likely to be found at relatively low frequencies in the overall population. There is also no comparison measure with changes in earlier decades that might address whether such change represents an acceleration of past trends. For example, researchers have long noted that more-automated plants employ relatively more-skilled maintenance workers (Woodward 1965).

Economists Bartel, Ichniowski, and Shaw (2000) and Shaw (2002) conducted qualitative case studies of plants in the medical devices (n = 8), valve (n = 5), and steel (n = 70) industries. Like Zuboff (1988), they argued that the use of IT in manufacturing places more information at the disposal of production workers for rapid decision-making and problem-solving and makes it possible and desirable to combine tasks and give workers responsibility for a broader segment of the production process. The result is greater use of high-performance work practices, such as the decentralization of decision-making, employee involvement in problem-solving and quality control, team organization, broader job duties, and greater training (Bartel, Ichniowski, and Shaw 2000, pp. 2, 11 f., 30; and Shaw 2002, pp. 5, 7, 13 f.).

However, the magnitude of these changes in worker skill requirements is difficult to determine. The researchers touch on both computer-specific and general human capital issues within occupations as well as the issue of automation and between-occupation shifts.

In many plants, the introduction of IT has meant that work is less physical and involves more operation of computer terminals, process monitoring, and troubleshooting, while robots, computer numerically controlled (CNC) machine tools, and automated production flows do the actual work of handling and transforming materials into products. Even in a nonautomated assembly process, computers and chip technology have increased product variety and complexity, requiring greater attention to quality (Bartel, Ichniowski, and Shaw 2000, p. 13). However, in some cases, computers automate some key quality control functions, relieving workers of some inspection and quality control tasks, albeit creating new opportunities for other forms of quality control (Bartel, Ichniowski, and Shaw 2000, pp. 10, 21, 26 ff.).

In the five valve plants, machinists now program CNC machines, but they note that the "sophisticated software" comes with "a simple graphical user interface," and "programming skills would take a relatively short time to learn compared to machining skills, thus they tend not to be a limiting factor" and are learned on the job (Bartel, Ichniowski, and Shaw 2000, pp. 20, 22 f.). Considering the diverse production jobs they observed in the different industries, the authors concluded that "[t]he increase in demand for computer skills is very modest. New computerized machines are run with graphical options that operators can be trained to utilize very quickly." (Bartel, Ichniowski, and Shaw 2000, p. 32).

The case of the steel workers, who now work in central computer control rooms rather than on the production line, seems to encapsulate their general argument: "While some increase in computer literacy is also needed, the critical change in skill sets is being able to respond to the new information processes," which involves greater decision-making responsibility regarding quality control and "fixing disruptions and breakdowns" (Bartel, Ichniowski, and Shaw 2000, p. 30). In the steel industry, "[t]he beauty of the introduction of computers in the workplace is that the software that integrates computers is so good that production workers do not require extensive computer skills…[but] the operators now have far more information than they did in the past" as a result of computerization (2002, p. 4).

Yet formal education requirements did not rise in any of the plants. Despite employer claims that workers must be intellectually flexible, able to be cross-trained on different jobs, and have problem-solving, communication, and teamwork skills, the jobs still require no more than a high school degree and traditional machinist qualifications in the case of the valve industry (Bartel, Ichniowski, and Shaw 2000, pp. 11, 13, 22 f.). Even though their educational requirements are unchanged, employers in the steel industry are now said to be "looking for an entirely different type of employee," whereas previously they did little to screen applicants. But some of the desirable worker characteristics cited, such as being responsible and reliable and having a "positive attitude" toward hard work and rewards, as well as the others noted above, seem to be traditional virtues and unlikely candidates for explaining the large growth in earnings inequality (Shaw 2002, p. 8). Shaw acknowledged that the skills "are difficult to observe and quantify" (2002, p. 25) and that their magnitude may not be great (2002, p. 23). Because these technologies did not increase educational requirements of production workers, they do not seem to be strong candidates for explaining the growth in the education premium, at least on the basis of changing cognitive requirements in the production workforce.

Although training requirements may have increased in the different industries Bartel and colleagues (2000) and Shaw (2002) studied, analyses using CPS training supplements for 1984 and 1991 indicated that changes in the incidence of and payoff to training in the economy overall do not account for any of the growth in wage inequality (Constantine and Neumark 1996).

The research seems to suggest that automation is eliminating less-skilled jobs. A number of plants increased output while cutting employment and implementing automated processes (Bartel, Ichniowski, and Shaw 2000, pp. 10, 15). However, in the valve industry, employment loss extended to skilled machinists, draftsmen who have been replaced by three-dimensional computer-aided design and manufacturing (CAD/CAM), and even engineers, as well as less-skilled operators who monitor machine operations after machinists set them up (Bartel, Ichniowski, and Shaw 2000, p. 23). In this case, SBTC is difficult to distinguish from a general reduction in labor requirements. The steel industry has used centralized computer controls, sensors, and automated materials handling devices to replace jobs that previously involved working on the production line to set controls, monitor flows and make adjustments, and handle materials (Bartel, Ichniowski, and Shaw 2000, pp. 26 ff.; and Shaw 2002, p. 3).

However, Shaw (2002) did not believe that IT and human resource practices were the most important reasons for the decline in labor demand in steel, which suffered a wave of plant closures in the early 1980s due to recession, long-term underinvestment, imports, outsourcing, and strong wage increases despite weak product demand during the recession. Other technological changes specific to the steel industry that reduced labor demand in the 1970s and 1980s included the introduction of continuous casters, which eliminated an entire stage of steel making, and a shift from integrated steel mills to less labor intensive steel minimills (Shaw 2002, pp. 19 ff.). Shaw noted that production worker wages in steel have remained virtually unchanged despite the introduction of IT and new human resource practices, and, consistent with Harrison and Bluestone's (1988) deindustrialization argument, she believed that the loss of highly paid manufacturing jobs played a greater role in the growth of inequality than IT (Shaw 2002, pp. 24 ff.).

Economists Levy, Beamish, Murnane, and Autor (1999) conducted a qualitative study of how onboard computers, computer testing and diagnostic equipment, and the use of microcomputers for databases and training affect the skill requirements of auto repair workers. They followed Zuboff (1988) in noting that the work becomes more abstract. One cannot learn how microelectronic systems operate or detect most faults through simple listening, observation, or learning by doing, as with mechanical systems. The job requires some new, formal knowledge of electronics (Levy et al. 1999, pp. 12, 15). Embedded microelectronics and greater overall complexity of vehicle systems increases the number of manual pages, diagrams, test operations, and level of abstract reasoning to be performed.

The researchers gave no detailed estimate of the level of training required for these new tasks, but a senior trainer at a regional training center operated by the manufacturer found that many auto technicians, often middle-aged, had problems reading or understanding the invisible logic of electronic circuitry. However, this finding may have been a transitory generational problem, and because the training courses lasted only a few days, the extent of the additional requirements is unclear. Nevertheless, the introduction of computers into auto repair requires greater reading and some new technical knowledge—basic electronics—from higher-level auto repair workers (Levy et al. 1999, pp. 20 ff.). Lower level technicians who handle more routine jobs, such as brake replacements and tuneups, do not work with electronic systems and are unaffected by computerization (Levy et al. 1999, p. 29). The study contains no breakdown of the relative numbers of higher and lower level technicians. Analyses of decennial census (1960–90) and CPS (1971–91) data indicate that growth in educational attainment for auto technicians has been no faster than the overall average for all workers, even during the 1980s, when computers and microelectronics were introduced into automobiles (Handel 2000, pp. 146 f.).

Autor, Levy, and Murnane (2000) studied the consequences of introducing a check-imaging system for back-office jobs in two departments of a large bank, routine deposit processing and exceptions processing. A state-of-the-art system installed in 1994 included optical character recognition (OCR) to scan handwritten checks and deposit slips to verify that the check amounts correspond to the total recorded on the deposit slip. By 1999, the system successfully read about 57 percent of all checks. A digital camera also photographs the checks.

The routine deposit department operates the OCR system and also employs data entry clerks who receive the digital images and enter information in case the OCR system cannot read the handwritten amounts. Once the OCR system or human clerks enter the data, the system automatically verifies that the check amounts and deposit slip total are consistent (Autor, Levy, and Murnane 2000, p. 8). If the two amounts do not match, the problem is sent to an "image balancer" in the department who examines the check and deposit slip images on a computer to resolve the discrepancy.

The human capital requirements for these jobs did not change greatly after the changeover; in both periods, most employees were female high school graduates. The image balancers had the highest skill requirements, and most of them were drawn from the existing workforce and given 36 hours of classroom training and two weeks of support from an experienced image balancer to learn the new system, "suggesting that modest amounts of training could impart the requisite computer skills" (Autor, Levy, and Murnane 2000, pp. 9, 11). The new check-processing technology improved productivity by 27 percent between 1994 and 1999 and had the potential to automate many data entry clerk positions out of existence. In practice, however, layoffs were avoided because of the increased volume of checks processed following the bank's acquisition of another bank during this time. However, the authors suspect that improvements in OCR software will likely eliminate more of these jobs in the future and will also allow more of the work to be outsourced to offshore data-processing operations. Changing bank regulations that permit banks to provide customers with check images instead of the original paper checks, to some extent responding to the new IT capabilities, will also likely eliminate low-skilled packaging jobs in the bank and filing jobs in corporate client firms in the future. The availability of records on the Internet may cut the number of customer service representatives as well (Autor, Levy, and Murnane 2000, pp. 12 f., 20).

The exceptions processing department handles issues such as insufficient funds, stop payment requests, signature verification for large checks, and possible fraud. The imaging technology eliminated previous bottlenecks, such as waiting for boxes of paper checks to be delivered from another department.

However, previous reorganization of the workplace appeared to have a more significant impact. Previously, different exceptions processors specialized in handling each type of problem, even though they were often interdependent in real situations and the narrow scope of each function hindered cooperation. The bank used the impending arrival of the new technology in the following year to reorganize the work along lines described by Zuboff (1988), giving workers responsibility for entire accounts, training them to solve all types of problems, and providing them with a more holistic understanding of the work process and customer needs. This reorganization accounted for two-thirds of the productivity gains between 1994 and 1996, and the new technology accounted for the remaining one-third. In total, the number of exceptions processors declined by 28 percent, from 650 to 470, achieved through attrition owing to a 30 percent annual turnover rate (1994–96). The bank promoted workers by one pay grade, increasing their wages from $10.64 to $13.50 (27 percent) in 1998 dollars, after they completed 40 hours of classroom training and 40 hours of on-the-job training to learn the different types of exceptions processing. The pay range was also widened in recognition of the increased skills required and scope for individual initiative, suggesting greater potential inequality within the occupation (Autor, Levy, and Murnane 2000, pp. 15 ff.).

The changes were partly reflected in stricter hiring standards. Computer skills were relatively easy to teach, but the reorganization of production required a more holistic or systems-level understanding of the different steps in exceptions processing and their interrelations. The greater weight placed on conceptual abilities, initiative, and problem-solving led to greater recruitment of college graduates, whereas previously most exceptions processors had been high school graduates, according to bank managers (Autor, Levy, and Murnane 2000, pp. 14, 19). The study presented no firm-level or CPS evidence on trends in the education of bank clerical workers that would test this conclusion more formally.

Autor et al. (2000) concluded that IT has the potential to automate routine low-skill jobs out of existence and enhance the value of more-skilled workers, consistent with the SBTC thesis. However, despite the surprisingly large pay raise, the role of IT in this process is ambiguous because so much of the productivity gain can be attributed to the earlier reorganization. Even in this case, the training was relatively short, although Autor et al. (2000, p. 19) followed Zuboff (1988) in arguing that computers facilitate this type of job redesign by consolidating information for the first time in unified databases easily accessible to front-line workers. According to this view, working with a computer increases the demand for general cognitive skills, such as problem-solving and intellectual flexibility, apart from application-specific computer knowledge.

However, another problem in interpretation is that this bank was one of the first to reorganize exceptions processing and introduce imaging technology in 1994, which does not coincide with the timing of earnings inequality trends. Inequality grew in the early to mid-1980s and stopped growing in the 1990s. If this generation of computers represents an acceleration of technological change and is representative of other trends in other sectors, its effects on the overall labor market are not immediately evident in national wage data. Because banking has a long history of computer use and magnetic ink character recognition systems, it is also possible that the trends Autor et al. (2000) describe represent a smooth continuation of trends in this industry visible across a number of decades rather than a qualitative break with past trends. To be compelling, one would need evidence of greater technological change in the 1980s than either before or since.

Siegel (1999) randomly surveyed 79 large manufacturing firms on Long Island, New York, in 1990, which accounted for 85 percent of manufacturing employment in the area. He examined the impact on employment of advanced manufacturing technology, including CAD/CAM, CNC, robots, automated guided vehicles, and material requirements planning systems, but also just-in-time inventory and statistical process control techniques. He found that advanced technology is associated with increased training, and followup interviews with firms also indicated a shift for production workers in the direction of greater use of teams, decision-making authority, broader jobs and multiskilling, data processing and analysis, and the use of programmable machines using customized software. These findings are consistent with Zuboff (1988) and others who claim that IT is associated with increased general human capital requirements, such as greater information processing, often as a result of the introduction of high-performance work practices (Siegel 1999, pp. 73, 84 ff.).

In addition, Siegel (1999) also found that firms adopting advanced manufacturing technology experienced employment losses (–5.8 percent), whereas nonusing firms grew (12.8 percent) between 1987 and 1990. The proportion of high-level white collar workers grew somewhat, whereas the share of clerical and production workers declined (Siegel 1999, pp. 67 ff.). The increased share of more-educated workers within industries that adopt IT is consistent with the SBTC thesis, although the shrinking employment in these industries would mitigate the effect on overall demand for educated labor in the economy as a whole.

To test for computers' effect on human capital requirements, Handel (2000, pp. 155 ff.) analyzed the association between computer use and education using the October CPS supplements on computer use (1984, 1989, 1993, 1997). Computer use was associated with slightly more than 1 year of education, controlling for gender, race, region, and other background variables; controlling for one-digit occupations cuts these estimates in half. Even accepting these estimates at face value, they indicate that computers are not typically leading to the replacement of high school-educated workers with college-educated workers or even workers with a junior college education. Computer use rose about 12 percentage points between 1984 and 1989 (see table 5), the only time during the 1984–97 period when wage inequality was still increasing, which implies that computers increased the demand for education by about 0.06–0.12 years. By comparison, mean education levels actually rose by 0.18 years during this period, suggesting that any impact could have been absorbed without generating the shortages of college-educated labor assumed by the SBTC thesis.

Even these estimates may be generous. The method just described leads to clear biases; for example, word processing and e-mail use are associated with an additional 0.4 years of education in 1997, whereas the effect of programming is less than half as large. When fixed-effects models of the change in education as a function of the changes in computer use within occupation groups are estimated, an increase in computer use of 1 percentage point between 1984 and 1989 is associated with an increase in mean education within occupations of 0.002 years. This finding implies that an increase in computer use of 12 percentage points would be predicted to increase an occupation's mean education by 0.024 years during this period, well below the actual increase of 0.18 years in mean education. An occupation that moved from having no computer users to 100 percent computer users is predicted to increase mean education by 0.2 years, well below even the lower-bound estimates in the individual-level models.

Finally, when the growth in computer use within occupations for the 1984–97 period is used to predict changes in within-occupation education for the 1971–76 period, a very similar association is present. Occupations with the greatest increases in computer use in the 1980s were already upgrading educational levels for other reasons long before the diffusion of computers. Therefore, although changes in computer use are associated with skill upgrading, the relationship is not likely to be causal. Autor et al. (1998, p. 1194) report similar results using their industry-level models.

The message of the studies favoring the SBTC thesis is that working with computers involves more intangible, symbolic, and information-intensive tasks, often enhanced by complementary organizational changes, but the actual difficulty levels of the new conceptual and literacy skills are still unclear. Indeed, studies that focus directly on high-performance work practices, such as those described by Fernandez (2001) and Bresnahan et al. (1999, 2002), have had difficulty discerning any effect on wages (Osterman 1994, 2000; Handel and Gittleman forthcoming), suggesting that the skill upgrading is modest. Other studies question the association of computer use and increased educational or general human capital requirements.

It seems clear that as microelectronics become embedded in more systems that were once exclusively electrical, mechanical, or based on other principles, those who must ensure they run properly, such as electrical maintenance workers or auto mechanics, will likely need some electronics knowledge. However, the actual additional demand to these workers' training and skills is also unclear, and the majority of jobs involving computers do not require knowledge of electronics.

To the extent that these studies posit general human capital effects as a consequence of working directly with computers, they also imply conceptually similar regression models as the thesis that computer use affects skill demands through computer-specific human capital requirements though they posit a different interpretation of the mechanism whereby computers affect skills and wages. When computer use coefficients are small or insignificant, as in several fixed-effects models described earlier, they call into question this view as much as the original view of the computer wage premium. More distinctive is the idea, also present in a number of the preceding studies, that computers have various indirect effects on general human capital requirements regardless of whether workers personally use computers. If these spillover or environmental effects affected users and nonusers equally, one would not expect indicators of direct computer use to reflect this impact.

Indirect Impact of Computerization Through General Human Capital

One of the leading arguments for SBTC claims that computers affect general human capital requirements indirectly by increasing the information content of work for nonusers and users in ways that are disconnected from the direct operation of computers themselves. Almost all of the case studies that focus on increased general human capital requirements fail to explicitly specify how nonusers might be affected. To the extent that these effects are concentrated among users, one would still expect the user/nonuser distinction to be salient even if the interpretation of wage differences between the groups no longer relies on the complexity of computer skills per se. Only if the effects were not felt disproportionately by computer users would one expect skills among nonusers to rise as much as among users and the basic computer wage premium model to be invalid. Some possible mechanisms can be inferred from studies reviewed in the previous section, such as the increased number of documents used in the automated production system Fernandez studied, which seems to have affected workers who did not interface with the automated equipment itself, but most research reviewed in this paper takes a more "black box" approach and is not explicit about the exact causal mechanism.

After the disappointment with the computer wage premium literature, the study by Autor, Katz, and Krueger (1998) attracted the greatest attention among those supporting the SBTC thesis of rising earnings inequality. As with Bresnahan et al. (1999, 2002), they "do not view the spread of computers as simply increasing the demand for computer users and technicians, but more broadly as part of a technological change that has altered the organization of work and thereby more generally affected the demand for workers with various skills" (Autor, Katz, and Krueger 1998, p. 1186).

To test this hypothesis, the authors used CPS data to calculate changes in computer use within industries to predict changes in the share of college-educated workers employed within industries to see whether a computer-rich environment (i.e., industry) is associated with a greater use of skilled labor. They found that industries that increased the proportion of workers using a computer between 1984 and 1993 also increased the proportion of college graduates and decreased the proportion of those with only a high school degree between 1979 and 1993 (Autor, Katz, and Krueger 1998, p. 1190).

The problem with these models is that an association between computers and more-educated labor need not reflect the presumed causal relationship; the lower price and greater availability of computers does not necessarily stimulate employers to seek more-skilled employees to use them. A strong possibility exists that both computer use and education levels within industries share a common dependence on changes in the occupational composition of employment within industries. As noted previously, computers are used most often by managers, professionals, and clerical workers; they have become standard office equipment. Any increase in office employment will result in increased use of computers, as well as telephones, copiers, fax machines, and pencils (DiNardo and Pischke 1996). Instead of modeling the demand for different types of labor as a function of the stock of office equipment, one can just as easily switch the independent and dependent variables using the same data to model demand for computers as a function of the changing level of white collar employment, which has increased throughout this century, prior to and independent of the diffusion of computers (Handel 2000, p. 167). Using computers as a predictor of the type of labor demanded requires an exogeneity assumption that is difficult to justify. In short, the direction of the causal relationship between computer use and a more-educated workforce is unclear.

Autor et al. (1998) tried to rule out reverse causation in two ways. In the less successful of these exercises, they found that the effect of average growth in computer use in the 1984–93 period predicted as rapid a rate of educational upgrading for 1970–80 as for 1980–90 and only somewhat slower rates for 1960–70. This finding suggested that industries with the greatest increases in computer use during the 1980s were already upgrading the educational levels of their workforce for other reasons before computerization and that the computer coefficient in the main models may be biased. Even if one argues that the variable measuring growth in computer usage between 1984 and 1993 is picking up a common underlying technological change variable in the 1970s and 1980s, the similarity of the coefficients suggests no evidence of acceleration of SBTC in the 1980s, whereas growth in earnings inequality was much faster in the 1980s compared with the 1970s (Autor, Katz, and Krueger 1998, p. 1194).

In addition, computers had the strongest effect on educational upgrading for 1990–96, which the authors seem to cite as evidence of an acceleration in the rate of SBTC, although earnings inequality stabilized during these years (Autor, Katz, and Krueger 1998, p. 1194). Indeed, in a preceding section of this study, Autor et al. (1998, pp. 1177 ff.) noted with some surprise that, by their measures, growth in demand for college graduates actually decelerated during the 1990s to levels lower than at any other time since the 1940s, despite the continued growth of computer investment. This finding suggests that if the IT revolution did have a skill impact, it is a thing of the past.

In fact, Autor et al.'s (1998) conclusions about the relative roles of supply and demand call into question the point of their subsequent computer-skill demand models because they showed that, although demand for college graduates accelerated somewhat in the 1980s, the deceleration in the relative growth of supply of college graduates was much more dramatic and important for inequality growth during this period (Autor, Katz, and Krueger 1998, pp. 1177 ff.; see also Katz and Murphy 1992). By this account, declining cohort size and stagnating college attendance rates would seem to play a greater role than IT. In short, many pieces of the puzzle do not fit together as neatly as the SBTC thesis implies.

In a second sensitivity analysis more favorable to the SBTC thesis, Autor, Katz, and Krueger (1998) used data from the National Income and Products Accounts to show that computer investment per worker in the previous 5 years was positively related to the use of more-educated workers in the following decade even after controlling for overall capital intensity (Autor, Katz, and Krueger 1998, p. 1197). This finding is stronger evidence for a causal relationship, but in similar analyses, Mishel and Bernstein (1998, pp. 335 ff.) showed no acceleration in the impact of either computers or capital intensity on educational upgrading within industries since the 1970s.

In a broader sense, Autor et al.'s (1998) study is unsatisfying because the causal mechanism accounting for the computer-educated labor association was not specified. The conceptual models seemed somewhat analogous to tests of neighborhood effects in poverty research, which investigated whether neighborhood conditions, such as poverty rates, affected individual outcomes independent of individual-level variables, such as income. By arguing for a contextual effect, Autor et al. avoided the controversies surrounding the computer wage premium literature, which examined the effects of an individual's own computer use on the individual's wages. Given the high correlation likely between rates of computer use within an industry and individual computer use, it is hard to see how the model as specified escapes this problem; an individual-level model that includes industry-level rates of computer use while controlling for individual computer use would seem to be more appropriate. On a more basic level, it is unclear exactly how having computers in one's industry might affect a job's skill requirements independent of one's own computer use. Autor et al. do not really explain the association they observe between computers and education within industries and why this model is preferable to one specified at the individual level.

Fernandez's (2001) work was more concrete and suggested the possibility that computers increase the information content of jobs—even jobs that do not involve using computers directly—by increasing the amount of paperwork, written documents, and quantitative data generated. Computers may also eliminate routine tasks and create more complex tasks in which high-skill involvement with computers plays only a small role. Finally, computers might increase the demand for more complex or a greater variety of novel products within an industry, which would in turn increase the demand for skilled labor.

In one of the few studies to specify such mechanisms, Levy and Murnane (1996) studied a bank's accounting services department, which kept the books for mutual and pension funds. Accountants needed to perform only a small set of the tasks taught to accounting majors, most of which the bank provided through on-the-job training combined with in-house training modules lasting about a week each. The bank recruited graduates from local second- and third-tier colleges with quite variable training in business and accounting; most of them had little computer knowledge beyond word processing, although the banks' software was user-friendly enough to pose little difficulty for them. Some bank staff debated whether the recruitment of college graduates for these positions reflected a demand for abstract reasoning, intellectual flexibility, maturity, and the ability to meet tight deadlines, or whether managers hired people with backgrounds similar to their own because they were easier for them to manage.

The growth in the size and complexity of mutual funds, itself driven partly by innovations in computer technology that supported greater trading volume and more complex financial services products, led to a nearly fourfold increase in employment in the accounting department between 1982 and 1993—a between-occupation shift. Levy and Murnane also found that computerization within the bank increased the skill required within accountants' jobs because routine computational, copying, and data entry tasks were no longer performed manually or with adding machines. The more complex aspects of the job, such as locating and fixing mistakes and performing more complex stock account valuations, now constituted a higher proportion of accountants' work time. Training was expanded and formalized into an 8-week, all-day program before accountants worked on actual accounts. However, the work remained repetitive and stressful, and turnover remained high.

In this case, working directly with computers does not require significant computer-specific or general skills, but computers have increased the demand for and variety of a service that was always relatively skill-intensive, generating a between-occupation shift and shifting the job's emphasis toward complex tasks. Thus, computers have had an indirect effect on the skill content of the job quite apart from the operation of computers per se. Qualifying this case somewhat is the lack of any apparent increase in formal educational requirements for the job, perhaps not surprising because the change primarily involved using previously required skills with increased frequency. The increased size of the accounting department might be expected to influence the demand for educated labor, but the changing character of the work does not seem to have had such an effect. Likewise, although the bank's training requirements appear to have increased, analyses using CPS training supplements for 1984 and 1991 indicate that changes in the incidence of and payoff to training in the economy overall do not account for any of the growth in earnings inequality (Constantine and Neumark 1996). In other words, it is not at all clear that the magnitude of the skill shifts within accounting is very large or sufficient to explain a significant fraction of the growth in earnings inequality. The researchers did not present information on the evolution of the wages paid by the firm for this job.

Indirect Impact of Computerization Through Job Creation and Displacement

Perhaps the most intuitive case for believing that high technology increasingly disadvantages the less skilled is the notion that it causes shifts in the distribution of workers between occupations; that is, its labor-saving qualities eliminate less-skilled jobs while increasing the number of more-skilled jobs. The limiting case in manufacturing is the unmanned or "lights out" factory, so named because the manufacturing process is so automated that it can be conducted in the dark. Advances in other computer processes raise the prospect of similar labor savings in other industries, such as check processing (Autor, Levy, and Murnane 2000).

Other examples of between-occupation shifts from studies discussed previously include the somewhat increased use of skilled maintenance workers in the automated plant studied by Fernandez (2001), the association of advanced manufacturing technology with declines in the share of production workers (Siegel 1999), declines in production labor in the steel and other industries (Bartel, Ichniowski, and Shaw 2000; and Shaw 2002), and the increased use of accountants as a result of the expansion of mutual funds (Levy and Murnane 1996). With the possible exception of check processing, however, some advocates of the SBTC thesis view the substitution of computers for labor as a relatively small part of the computer-induced shift in demand toward more-skilled workers (e.g., Bresnahan, Brynjolfsson, and Hitt 1999, pp. 11 f.).

An early study found that computers reduced the numbers of both clerical workers and managers within industries between 1972 and 1978, although the effect was somewhat larger for clerical workers and was offset somewhat for both groups with resumed growth in these groups over time (Osterman 1986).

One of the strongest claims for technological displacement of less-skilled jobs came from Berman, Bound, and Griliches (1994, pp. 368, 374), who noted that between 1979 and 1989, the employment of production workers in manufacturing declined from 14.5 to 12.3 million (15 percent), while nonproduction employment rose from 6.5 to 6.7 million (3 percent) and output rose markedly. Using industry-level data from the Annual Survey of Manufactures, the authors found that computer investment within manufacturing industries was associated with relative declines in production worker employment and accounted for more than 40 percent of the change within industries in the proportion of the total wage bill going to production and nonproduction workers respectively between 1977 and 1987 (Berman, Bound, and Griliches 1994, p. 388). They cited BLS case studies that indicated that computers have eliminated production workers who performed typesetting in printing and publishing and NC/CNC machine tools and robots that have replaced production workers with technical workers and professionals (Berman, Bound, and Griliches 1994, p. 390).

International evidence indicated that the share of nonproduction workers within manufacturing industries declined in about a dozen industrialized nations in the 1980s, even though the relative wages of nonproduction workers usually rose during this time. However, the authors acknowledged that whether this decline represented an acceleration relative to the 1970s was unclear (Berman, Bound, and Machin 1998, pp. 1257 ff.). Using manufacturing industries as the unit of analysis, the authors correlated increases in the share of nonproduction workers across industrialized nations by industry. They found the correlation between the United States and five other countries (Sweden, the United Kingdom, Belgium, Finland, and Denmark) to be roughly 0.5, but the correlation was only about 0.25 or less for the United States and three other countries (Australia, Japan, and Austria) for the 1980s. Thus, many of the same industries experienced above-average increases in the nonproduction worker share in both the United States and other industrialized countries, which the authors interpreted as suggesting some common trend in production technology.

Cross-country correlations of within-industry changes between the United States and other nations were much weaker for the 1970s, but this was not necessarily the case for the correlations among the other countries. Because industry was measured using only 28 categories, with a high potential for noise given varying national industrial classification systems, the authors argued that the cross-country correlations were strong evidence for a common variable, technological change, that decreased the demand for unskilled labor within the same industries across nations (Berman, Bound, and Machin 1998, pp. 1265 ff.).

There are a number of qualifications to these results. As with Autor et al. (1998), ruling out reverse causation is difficult. Computers became a standard piece of office equipment in the 1980s, and any growth in the white collar workforce would seem to require additions to the stock of computers, not to mention desks and office chairs. It is not clear that the increase in the availability of computers stimulated the hiring of nonproduction or office workers rather than the reverse.

Berman et al. (1994) acknowledged that the recent growth in the nonproduction share of employment in manufacturing is not unique. Although the growth in the proportion of nonproduction workers seems to accelerate over time, rising 0.05 percentage points per year between 1959 and 1973, 0.23 percentage points per year between 1973 and 1979, and 0.38 percentage points per year between 1979 and 1989, it rose most rapidly—0.95 percentage points per year—between 1947 and 1958 (Berman, Bound, and Griliches 1994, p. 392). At the conclusion of their study, which made strong claims for the importance of computers, Berman et al. suggested that "we avoid exaggerating the uniqueness of the computer revolution" (1994, pp. 392 f.).

Indeed, decennial census data for the entire economy show that between 1950 and 1990, the percentage of operatives and laborers declined at a roughly constant rate from about 26 percent to less than 15 percent of the workforce, whereas the percentage of craft workers declined from about 14 percent to about 11 percent between 1970 and 1990, with no sign of acceleration between 1980 and 1990 (Handel 2000, p. 167).

In addition, Howell (1995) noted in an early comment on Berman et al. (1994) that nearly all of the shift toward nonproduction workers in manufacturing that they cite for the 1979–89 period occurred between 1979 and 1982 (Howell 1995; Berman, Bound, and Griliches 1994, pp. 370, 372). Indeed, flatness in the nonproduction share of manufacturing employment persisted at least through 1997 (Handel 2000, p. 301). Howell further noted that it is hard to understand how computers or advanced manufacturing technology could be the primary source of changes in the occupational distribution within manufacturing before 1983 and have little effect afterward because the National Income and Product Accounts indicate that computer investment in manufacturing did not take off until after 1983 (Howell 1997, pp. 14 f.). To meet this concern, one would have to estimate the models in Berman et al. separately for both the early 1980s and the post-1983 period.

CPS data show a faster decline in the share of operatives and laborers within manufacturing between 1966 and 1976 than between 1985 and 1997, and the stability in employment share since the late 1980s is also associated with stability in relative hourly wages, suggesting a state of equilibrium rather than wage declines propping up employment (Handel 2000, pp. 301 f.).

Doms, Dunne, and Troske (1997) used matched data from the Department of Commerce's Survey of Manufacturing Technology (SMT) (1988, 1993), Longitudinal Research Database (LRD), Census of Manufacturers (1977, 1992), and the 1990 decennial census to examine the relationships between technology and worker skill while controlling for establishment characteristics such as size, plant age, industry, and the capital-to-output ratio. The SMT covers a limited number of industries (SIC 34–38) but has unusually rich technology measures, with detailed data on the use of 17 manufacturing technologies, such as CAD/CAM, NC/CNC machine tools, robots, programmable logic controllers, factory LANs, microcomputers on the factory floor, automated storage and retrieval systems, automated guided vehicles (AGVs), and flexible manufacturing systems. The authors hypothesize that such technologies require greater literacy skills, consistent with Zuboff, and skilled support staff to maintain them, such as IT professionals, as well as altering the occupational composition more broadly (Doms, Dunne, and Troske 1997, p. 260).

In cross-sectional regressions, Doms et al. (1997) found that plants using more high-technology equipment also use more scientists and engineers and, to a lesser extent, managers and craft workers. These plants also have more-educated production and nonproduction workers. However, contrary to Berman et al.'s (1994) study, the percentage of nonproduction workers and their share of the total wage bill were not associated with the number of technologies used in a plant, although the authors caution that this finding may be an artifact of their subsample.[5] The presence of technology in an establishment was not associated with higher wages for managers and professionals. Plants using seven or more technologies did pay higher wages to production workers,

[5] Only about 350 out of 9,400 plants in the SMT can be matched to LRD and census data.

most of which was explained by the production workers' higher levels of formal education (Doms, Dunne, and Troske 1997, pp. 262 ff.).

However, it is not clear whether any of the significant cross-sectional relationships between technology use and occupational composition, skill, and wages are causal or reflect omitted variables, such as firm resources or management quality, that are responsible for the observed association. Using matched data for 3,260 plants from the Census of Manufacturers for 1977 and 1992 and the SMT (1993), Doms et al. (1997, pp. 273 ff.) found that the adoption of advanced technologies had no effect on changes in nonproduction workers' share of the total wage bill, labor productivity, and production and nonproduction worker wages. A separate capital intensity variable was positively associated with all except nonproduction worker wages. These results are robust to a number of alternative specifications, including models that look specifically at the effects of technologies controlling production processes directly (e.g., robots and AGVs) as opposed to information-processing technologies (e.g., CAD and, LANs).

Additional analyses indicate that the use of advanced manufacturing technology in 1993 had as strong an association with productivity and production worker wages in 1977 as in 1992 and little or no association with nonproduction worker wages and share of the total wage bill in either year (Doms, Dunne, and Troske 1997, pp. 278 f.). Cross-sectional associations among technology, occupational composition, skills, and wages seem to reflect establishment fixed effects rather than the effects of technology adoption per se. Plants with somewhat more-skilled and better-paid workers were more likely to adopt the new technologies rather than vice versa, and the adoption of advanced manufacturing technology did not alter the wage or occupational structures within plants. This finding suggests that firm resources or management quality may be the cause of both a constant level of worker quality and decisions to adopt technology, whereas the association between technology adoption and workers' skills is spurious.

One potential problem with these longitudinal analyses is that they are a sample of plants that existed throughout the 1977–92 period. It is possible that plants failing in that period would have paid lower wages and employed a larger proportion of production workers in 1992 than both technology adopters and nonadopters whereas new plants founded after 1977 might show the opposite pattern, which might yield greater support for the SBTC theory.

Interestingly, a plant-level measure of computer investment in 1992 from the Annual Survey of Manufactures (ASM) was associated with increases in nonproduction labor, consistent with Berman et al.'s (1994) industry-level study using the ASM. However, the authors acknowledged that these increases may merely show that office workers are more likely to use computers rather than that the greater availability of computers stimulated the hiring of more office workers (Doms, Dunne, and Troske 1997, p. 280).

The causal interpretation is also a bit paradoxical because Berman et al. (1994) make clear that the main reason for the growing proportion of nonproduction workers in manufacturing is the large *decline* in the absolute number of production workers, not the small growth in the number of nonproduction workers. Yet one would expect the factory automation technologies in the SMT to be the most likely to displace production labor because they "are directly used in the production of manufactured goods, whereas computing equipment is often a main tool of managerial and clerical labor" (Doms, Dunne, and Troske 1997, p. 256). The notion that computers would eliminate large numbers of production jobs, whereas factory automation technologies would not, seems unlikely.

Taken together, results from Berman et al. (1994), Howell (1997), Handel (2000), and Doms et al. (1997) suggest that although the share of production workers in American manufacturing declined significantly during the early 1980s recession, the evidence is unconvincing that computers and factory automation have been substituted extensively for production labor or that computers are responsible for changing the occupational composition within manufacturing by stimulating the hiring of large numbers of nonproduction workers in manufacturing.

In addition, Doms et al. (1997) found that computer investment is not associated with changes in wages for any groups of workers, further weakening the case for a computer wage premium; that is, within-occupation skill shifts (Doms, Dunne, and Troske 1997, pp. 280 f.).

Although most studies treating between-occupation skill shifts focus on manufacturing, others point to the possible effects of automation in the service sector. In arguing for the SBTC theory of earnings inequality growth, Danziger and Gottschalk (1995, p. 141) suggested some possible sources of automation-driven changes in the occupational and skill composition of service jobs:

> [Beginning in the 1980s f]irms substituted computers and more-skilled workers for lower-skilled workers whose tasks could now be performed more efficiently with computers. Insurance companies could lay off file clerks…[and] checkout clerks no longer had to enter prices in the cash register. Inventory control was simplified and reordering could be done automatically. In these and other ways, technology (or automation) decreased the value of the skills of workers with lower levels of education and increased demand for workers with more education.

However, Danziger and Gottschalk (1995) did not actually investigate whether IT has had the labor-saving consequences they suggest. Handel (2000, pp. 177 ff.) examined trends between 1971 and 1997 in the proportion of workers in occupations that are likely to be most sensitive to technological changes using Current Population Survey (CPS) data.

Some trends are consistent with Danziger and Gottschalk's (1995) intuitions. The share of clerical workers in banking and insurance held steady in the 1970s and then declined from about 50 percent of employment in these industries to 40 percent between 1982 and 1997, consistent with a smooth substitution of technology for this type of labor.

Clerical workers' share of the overall workforce declined for the first time in the 20th century from 16.9 percent in 1983 to 14.1 percent in 1997, but this decline was concentrated mostly between 1986 and 1989 and 1992 and 1997, after most of the growth in earnings inequality occurred.

Other trends are not consistent with popular preconceptions. After increasing in the 1970s, the share of bank tellers in the banking industry dropped between 1981 and 1982 and changed little through 1997 despite the spread of automatic teller machines; tellers made up 20.6 percent of banking workers in 1971 and 18.0 percent in 1997. Despite the increased use of automatic letter-sorting machines, barcodes, and OCR, clerks in the Postal Service declined only slightly between 1983 and 1997 and the trend represents a deceleration compared with the 1971–79 period. Operators declined dramatically as a share of telephone workers between 1971 and 1977, from 21 percent to 4 percent, but the rate of decline was four times faster in the 1970s than the 1980s and 1990s. However, telephone installers and repairers declined from 32 percent of all telephone workers in 1971 to 17.4 percent in 1997, and this decline accelerated in the 1980s and 1990s, suggesting that improvements in telephone switching equipment and computer-based diagnostics and line repair may have played a role.

The share of cashiers among all grocery workers was no smaller in 1997 than in the late 1970s, before the introduction of barcode scanners. Shipping, stock, and inventory clerks as a share of workers in retail and wholesale declined faster in the 1970s than the 1980s and 1990s despite the emergence and spread of electronic data interchange and just-in-time inventory methods. Although many suggest that e-commerce and the Internet may eventually automate or replace many types of retail jobs with self-service (Hecker 2001), computer, communications, and microelectronic technologies do not yet appear to have had much of a labor-displacing effect.

Perhaps most surprising, despite the fact that the auto industry is the most intensive user of robotics, particularly in welding and paint operations, the share of welders and painters in the auto industry increased from 4 percent to 7.6 percent between 1983 and 1997, despite the presumed direct labor saving impact of these technologies. There may be tendencies toward both technological displacement in large firms and increased outsourcing to more labor-intensive subcontractors that offset one another. Nevertheless, according to both the March and Outgoing Rotation Group CPS series, robots and automation seem to have had no overall effect on the employment of welders and painters in the auto industry. Decennial census data suggest a modest decline, but there is little difference between the rates of decline in the 1970–80 period and the 1980–90 period.

Chapter 8: Conclusion

This review discussed several causal paths by which computers might conceivably affect the labor market, the demand for skill, and earnings inequality:

- Large-scale job displacement and unemployment.
- Increased demand for IT professionals.
- Broad increases in demand for computer-specific human capital.
- Broad increases in demand for general human capital among computer users.
- Broad increases in demand for general human capital felt equally among users and nonusers.
- Changes in the occupational composition of employment resulting from the automation of less-skilled jobs or the creation of more-skilled jobs.

Whereas the first claim is easily shown to be incorrect, the others are subject to substantial controversy. Clearly, research on the effects of IT on employment and work remains unsettled. Results that seem to show a strong relationship among technology, skills, education, occupation, and wages often appear more fragile on closer scrutiny. Many intuitive propositions find only imperfect support in research studies, and there are numerous anomalies and contrary research results. The fact that wage levels rose at the bottom of the distribution, inequality moderated, and unemployment fell to its lowest level in 30 years in the late 1990s, even as IT investment surged and Internet use burgeoned, suggests the need for caution in drawing conclusions about the effects of computers on the labor market.

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